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Study of Efficient Link Adaptation Schemes in Wireless Orthogonal Frequency Division Multiplexing (OFDM) Systems

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Study of Efficient Link Adaptation Schemes in Wireless Orthogonal Frequency Division Multiplexing (OFDM) Systems

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Dedicated to my family with all my heart.

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Wireless communication systems require high spectral efficiency and throughput in order to be cost-effective. Link adaptation schemes are known to be a good solution to achieve this goal. However, the necessity of additional information or increased complexity prevents these schemes from being implemented. In this context, research on resource allocation based on different constraints, such as complexity or feedback, is important.

The major contribution of this dissertation is the development of three novel techniques to enhance performance in practical implementations of the adaptive OFDM systems. This dissertation first introduces a new multiuser OFDM system to enhance performance in the low SNR regime. In this scheme, multiuser diversity can be efficiently amplified from random power allocation and opportunistic scheduling. Higher spectral efficiency can be achieved without an increase of complexity or feedback amount compared to conventional

multiuser OFDM systems using equal power allocation. This dissertation also presents a modified multi-mode power loading scheme. A modified multi-mode power loading scheme can circumvent the limit of current multi-mode power loading schemes by significantly reducing search amount from $2^N - 1$ to N, where N is the number of subcarriers. Finally, this dissertation has introduced adaptive OFDM systems using channel gain order information in limited feedback environments. Adaptive OFDM systems using the order mapping technique achieve comparable performance to conventional adaptive OFDM systems in terms of bit error rate and average spectral efficiency, while the amount of feedback is significantly reduced. Furthermore, by simply exploiting order mapping and interpolation, the analyzing technique circumvents the practical shortcomings of previous limited feedback techniques for OFDM systems.

Table of Contents

List of Tables

List of Figures

Chapter 1

Introduction

1.1 Overview

Innovative progress in wireless communication technologies during the last decade has had a major impact on human society and economy. While early wireless communication systems focused on low data rate services, such as voice services [1, 2], current wireless communication systems are focused on high data rate services, such as multimedia services [3, 4]. Moreover, the applicable range of wireless data communication systems has expanded from single cellular systems to multi-cellular systems [5, 6]. Data communication technologies that have mainly deployed in wireless local area network (WLAN) [7–9] are now expected to be used in multi-cellular environments. The key requirement to achieve the needed high data capability is the increase of spectral efficiency over wireless channels that suffer from fading. Orthogonal frequency division multiplexing (OFDM) [10] is one popular solution for high data capability in wireless communication systems. OFDM is multicarrier data transmission. In OFDM, a single data-stream is transmitted over a number of closely-spaced orthogonal subcarriers. The data-stream is divided into several parallel data streams or subcarriers, one for each subcarrier. While classical frequency division multiplexing (FDM) uses N nonoverlapping subcarriers

Table 1.1: The advantages and disadvantages of OFDM

The Advantages
High spectral efficiency
Robustness against inter symbol interference (ISI)
Robustness against frequency selective fading and narrow-band interference
Simple implementation using FFT
Low sensitivity to time synchronization errors
Simple equalization
The Disadvantages
High peak-to-average-power ratio (PAPR)
High sensitivity to frequency synchronization problems
High sensitivity to Doppler shift
Inefficiency caused by Cyclic prefix/Guard interval

to eliminate inter-channel interference, OFDM uses N overlapping subcarriers whose orthogonality removes inter-channel interference where N is the number of subcarriers. OFDM has been applied in many wideband digital communications such as digital television and audio broadcasting, wireless networking and broadband internet access. The advantages and disadvantages are listed in Table. 1.1.

This multi-carrier modulation scheme has been a great success in WLAN systems and has been adopted as the main transmission technology of various fourth generation wireless communication standards [11–13] because its inherent characteristics make it possible to provide high data rate services, such as multimedia services, in multicellular systems.

Transmission of channel state information (CSI) [14] between transceivers is one of key issues in meeting the requirement of high spectral efficiency in OFDM systems in order to be cost-effective [15–19]. By using CSI, spectral efficiency in various OFDM systems can be effectively enhanced by a link adaptation scheme that allocates power and determines modulation and coding level adaptively to the time varying channel [20–24]. Moreover, a link adaptation scheme in conjunction with CSI can also be exploited to amplify multiuser diversity gain with multiuser scheduling [21, 25–28]. However, the requirement of the exact CSI for link adaptation schemes normally necessitates a large feedback amount, which prevents practical implementation because wireless communication is likely to take place in a limited feedback environment [29–32]. Furthermore, implementation is also limited due to the additional complexity required in order to optimally allocate resources, such as power, frequency, and modulation levels. In this context, current research is focused on the practical constraints for wireless OFDM systems, especially feedback amount and implementation complexity [33–37]. In addition, research has been especially focused on performance enhancement in the low signal-to-noise ratio (SNR) or signal-to-interference-plus-noise ratio (SINR) regimes, which largely determine the performance of systems.

1.2 Proposed Research and Contributions

The primary purpose of this study is to develop novel and practical techniques for link adaptation schemes for wireless OFDM systems in the context of the practical constraints on complexity of implementation and amount of feedback. The following subsections briefly summarize assumptions that are used throughout the dissertation and that underline the three proposed techniques to achieve the goal of link adaptation for wireless OFDM systems: random waterfilling for multiuser OFDM systems, modified multi-mode power loading scheme, and adaptive OFDM systems using order mapping.

1.2.1 Summary of assumptions in this dissertation

Although each chapter describes a number of different assumptions for each proposed scheme, there are a number of fundamental assumptions contained in this dissertation that will be summarized in this subsection.

- A single cell environment that one base station covers is assumed. Additionally, interference from other cells or users is assumed to be lumped into the additive white Gaussian noise or is not considered.

- Perfect quantization is assumed. Although quantization error is one critical factor in deciding communication performance, this dissertation focuses on channel estimation techniques with assumed perfect quantization in order to fairly compare the effectiveness of each reconstruction method. The effect of quantization errors is discussed in Section 4.5.3

- Perfect sample and symbol synchronization are assumed to have been achieved by appropriate training sequences.

- Equally spaced pilot structure is assumed in the analysis. A properly chosen equally spaced pilot structure is optimal for the capacity of OFDM systems [38–40]. In this context, this study analyzes proposed schemes with equally spaced pilot structures. However, a discussion of performance with non-equally spaced pilot structure will be presented in Section 5.4.2.1

- Stationary fading channel models and slow fading environments are assumed.

- Sufficient cyclic prefix length to prevent inter-symbol interference is assumed.

- For multiuser OFDM systems, it is assumed that each user experiences fading independently.

- For Ch. 2 and 3, all the subchannels are independent and identically distributed (i.i.d). On the other hand, correlated channels are assumed for Ch. 4 and 5.

1.2.2 Random Waterfilling for Multiuser OFDM Systems

As wireless communication systems have become more popular, accessible spectrum has been occupied by many wireless systems. Hence, regulated frequency bands with appropriate operating SNR levels have been decreasing in availability. The decrease of available frequencies can be resolved by the following two strategies. First, totally new frequency ranges, such as *Millimeter-Wave Bands* [41, 42], can be used so as not to interfere with the frequency bands occupied by conventional wireless communication systems. The greatest challenge for the practical deployment of this solution is to develop devices that work reliably at high frequencies. Second, the system can be overlaid on top of licensed and/or unlicensed frequency bands, such as the industrial, scientific and medical (ISM) band. Ultra wideband (UWB) systems [43, 44] based either on Impulse Radio [45–48] or Multi Band OFDM [49–52] are in this category. The transmit power levels of these systems are regulated to be very low in order to minimize co-channel interference.

As a solution to frequency deficiency problems, this study focuses on the second category of the above strategies. This research proposes a new random waterfilling power allocation scheme for performance enhancement in clustered orthogonal frequency division multiple access (OFDMA) systems in a low SNR regime. The proposed random waterfilling enhances multiuser diversity and achieves higher throughput than static equal power allocation without an increase of complexity or feedback in a low SNR regime. Through simulations and mathematical analysis, this research shows that the relative gain over static equal power allocation increases as the received SNR decreases.

1.2.3 Modified Multi-mode Power Loading Scheme for Large Dimensional OFDM Systems

Multi-mode power loading [53] is a power loading algorithm based on the on-off configurations of subcarriers, where the transmitter equally allocates its available power only to the subcarriers indicated as “on”. Multi-mode power loading is an attractive power loading technique, since it avoids iterative procedures and periodic updates of threshold values in order to find the best power loading configuration. Multi-mode power loading achieves comparable spectral efficiency to optimal waterfilling with full CSI, while using only N feedback bits, where N is the number of subcarriers. The requirement of $2^N - 1$ brute-force searches, however, makes multi-mode power loading infeasible for large N. Research has shown that multi-mode power loading is plausible only when N is around 10 considering the complexity of the brute-force searches [53].

This study in Ch. 3 proposes a new power loading technique to generate the same optimal power loading configuration as the multi-mode power loading technique without recourse to brute-force searches. The proposed technique requires only N searches and a total of $N \log_2 N$ operations while the multi-mode power loading necessitates $2^N - 1$ brute-force searches. Thus, the new method works well with large N on a practical level. Sorting subchannel gains makes lower complexity possible. Although the idea of sorting subchannel gains was introduced previously [54], this study exploits the sorting in a novel way. In addition, the proposed technique does not need a shared codebook, so it is able to save the memory space for the codebook at the transceiver.

1.2.4 Adaptive OFDM Systems Using Order Mapping in Limited Feedback Environments

OFDM systems have been widely deployed to meet the requirements of high data rates. Many technologies incorporating OFDM have been studied in attempts to achieve higher spectral efficiency [24, 55–61]. Among those techniques enhancing the performance of OFDM systems, channel adapted techniques, such as power loading and adaptive coded modulation or adaptive modulation and coding [17, 57, 62–67], have been popular and effective in frequency selective fading channels. The basic concept of these adaptive OFDM systems is to achieve optimal throughput by adaptive variation of the transmitted power level, the constellation size, coding technique, or any combination of these based on channel variations. For this reason, the performance of adaptive OFDM systems is highly dependent on the accuracy of channel estimation at the receiver. In this context, full CSIT [68] is most desirable, but a limited spectrum usage of feedback restricts the use of full CSIT.

In limited feedback environments, a simple but practical approach for channel estimation is the use of comb-type channel knowledge [39, 69–74]. Although the comb-type pilot structure can efficiently reduce the amount of feedback, the amount of feedback information required to determine an appropriate modulation and coding level is still a burden in a limited feedback environment because emerging OFDM systems, such as [11, 12], exploit very broad spectrums. Besides the large amount of feedback, other practical shortcomings, such as high complexity at the mobile station [53, 75], quantization error [76, 77], and applicability limited to only small dimensions [53], need to be overcome.

To circumvent the practical shortcomings of previous adaptive OFDM techniques using limited feedback, this dissertation proposes a new adaptive OFDM system using order information of the subcarrier channel gains. Analysis shows that adaptive OFDM systems using an order mapping technique achieve comparable performance to conventional adaptive OFDM systems in terms of bit error rate and average spectral efficiency, while the amount of feedback is significantly reduced. Furthermore, by simply exploiting order mapping and interpolation, the proposed technique overcomes the practical shortcomings of previous limited feedback techniques for OFDM systems. The advantages are particularly visible at low SNR or for many subcarriers, both of which will be very common in the emerging wireless broadband OFDM standards.

1.3 Organization of This Dissertation

This dissertation is organized as follows. Chapter 2 investigates the techniques used in overlaid systems operating in occupied frequency bands, such as ISM band and UWB systems. It also proposes a random waterfill power allocation scheme for clustered OFDMA systems and shows that the relative gain over static equal power allocation increases as the received SNR decreases. Chapter 3 proposes a modified multi-mode power loading scheme. In this chapter, first the conventional multi-mode power loading is briefly explained. Then an advanced multi-mode power loading technique that significantly reduces the required search amount from $2^N - 1$ to N is introduced. In chapter 4, a new adaptive OFDM system exploiting order mapping is proposed. The performance of various channel estimation schemes is compared, as well as the required feedback amount. Chapter 5 extends the analysis of OFDM systems using OM technique to adaptive OFDM systems including AMC per subcarrier and cluster. Multidimensional coded variable-rate M-QAM given in [78] is considered for AMC. Finally, chapter 6 concludes the technical contents of this dissertation and briefly introduces future work.

1.4 List of Acronyms and Abbreviations

3GPP-LTE	:	Third Generation Partnership Project
ACM	:	Adaptive Coded Modulation
AMC	:	Adaptive Modulation and Coding
ASE	:	Average Spectral Efficiency
AWGN	:	Additive White Gaussian Noise
BER	:	Bit Error Rate
bps	:	bit per second
BS	:	Base Station

CQI	: Channel Quality Indicator
CSI	: Channel State Information
CSIT	: Channel State Information at Transmitter
DL PUSC	: Downlink Partially Used Subchannelization
EQP	: Equal Power Allocation
E-UTRA	: Evolved UMTS Terrestrial Radio Access
FFT	: Fast Fourier Transform
IFFT	: Inverse Fast Fourier Transform
IID	: Independent and Identically Distributed
ISI	: Inter Symbol Interference
JPOS	: Joint Polling and Opportunistic Scheduling
MIMO	: Multiple Input Multiple Output
MSE	: Mean Squared Error
MQ scheduling	: Maximum Quantile Scheduling
NMSE	: Normalized Mean Squared Error
OFDM	: Orthogonal Frequency Division Multiplexing
OFDMA	: Orthogonal Frequency Division Multiple Access
OM	: Order Mapping
QAM	: Quadrature Amplitude Modulation

QoS	: Quality of Service
PAPR	: Peak to Average Power Ratio
RWF	: Random Waterfilling
SINR	: Signal to Interference plus Noise Ratio
SNR	: Signal to Noise Ratio
UWB	: Ultra Wide Band
WLAN	: Wireless Local Area Network
WirelessMAN	: Wireless Metropolitan Area Network
WiMAX	: Worldwide Interoperability for Microwave Access
WSRmax	: Weighted Sum Rate Maximization
WSPmin	: Weighted Sum Power Minimization

Chapter 2

Random Waterfilling Exploiting Multiuser Diversity for Clustered OFDMA Systems

2.1 Introduction

As wireless communications have become more popular, regulated frequency bands with appropriate operating SNR levels have been decreasing in availability. The deficiency of available frequency allows the emergence of overlaid systems operating in occupied frequency bands such as industrial, scientific and medical (ISM) band and Ultra Wideband (UWB) systems based either on Impulse Radio [45–47] or Multi-band OFDM [49–51]. The transmit power levels of those systems are regulated to be very low in order to minimize co-channel interference. Thus, the overlaid systems typically operate in the low received SNR regime and rely on high spreading or combining gains from wide bandwidth. For a given spreading gain or combining gain, improving spectral efficiency in the low received SNR regime is a key issue in overlaid systems.

This chapter focuses on capacity enhancement for multiuser OFDM operating in a low SNR regime. In multiuser OFDM, per-subcarrier user assignment maximizes the sum capacity, but it is prohibitive in practical implementations due to its high complexity. As a practical alternative, clustered subcarrier allocation has been widely adopted in multiuser OFDM systems, where the subcarriers are divided into several clusters, and each cluster is allocated to a user based on an appropriate scheduling policy [11, 79–81]. If opportunistic user scheduling described in [27] is adopted, system throughput significantly increases due to multiuser diversity gain. In addition to opportunistic user scheduling, adaptive power allocation (or power loading) over a cluster efficiently improves the capacity of clustered multiuser OFDM systems. When full channel state information is available at the transmitter (CSIT), waterfilling power allocation across multiple subcarriers is the optimal strategy [82–84]. However, the requirement of the exact CSIT and high computational complexity of waterfilling prevents practical implementations. So many multiuser OFDM systems simply employ equal power allocation [85] along with opportunistic user scheduling to circumvent the difficulties of obtaining full CSIT [26]. Furthermore, equal power allocation across subcarriers is known to be optimal if no channel state information is available at the transmitter [86].

In clustered multiuser OFDM systems employing equal power allocation and opportunistic user scheduling, each user feeds back quantized information of their achievable rate or channel quality for each cluster. Then, the home base station (BS) opportunistically assigns each subcarrier cluster to the user with the best achievable rate. Equal power allocation provides reasonable performance if the SNR is high, but the performance gap between optimal waterfilling and equal power allocation increases as the SNR decreases because adaptive power allocation to varying channels is more crucial when SNR is low [87]. Therefore, equal power allocation is not an effective scheme in a very low SNR regime.

In this chapter, a novel power allocation scheme applicable to clustered multiuser OFDM systems is proposed. The proposed scheme achieves higher throughput in the low SNR regime than equal power allocation scheme, while maintaining similar implementation complexity. Additionally, the proposed scheme does not increase the amount of feedback information compared to the equal power allocation with opportunistic user scheduling. The proposed scheme is named *random waterfilling* [88], where power is randomly allocated to subcarriers in each subcarrier cluster, and then each cluster is assigned to the user with the highest achievable rate. If there are sufficient users, it is likely that there is a user whose randomly allocated power configuration is close to the optimal waterfilling power allocation. The proposed clusterwise random waterfilling amplifies multiuser diversity through this near-optimized power allocation.

2.2 Prior Work

Multiuser resource allocation for downlink OFDMA systems has been actively studied. Fig. 2.1 summarizes significant research results in this research area. The proposed scheme in this chapter focuses on the performance enhancement of open loop resource allocation, which is both practical and near

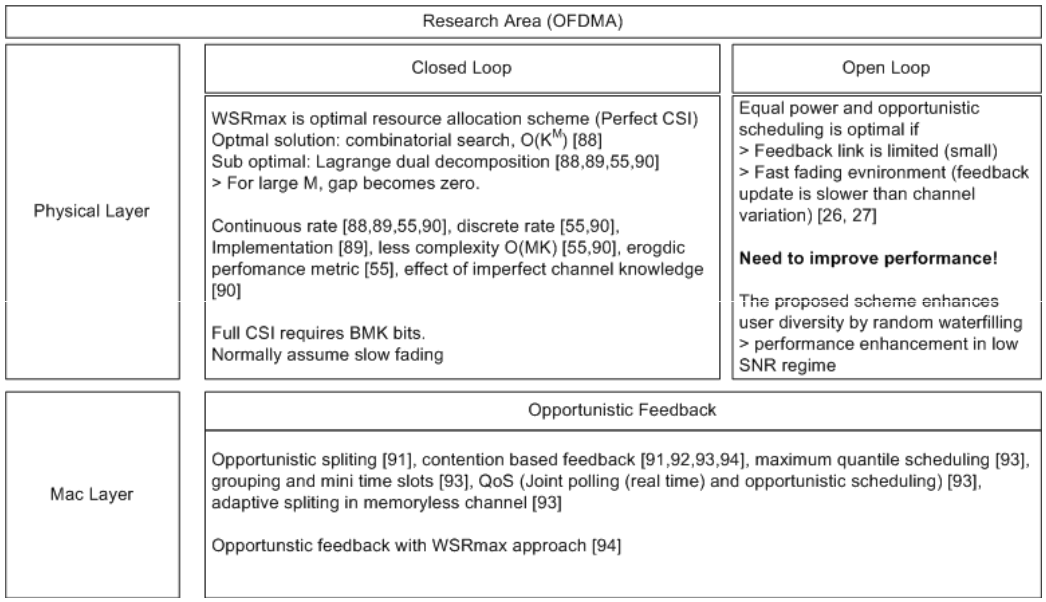

Figure 2.1: Summary of fundamental research results in OFDMA resource allocations

optimal for the limited feedback and reduced complexity requirement considered in [26, 27]. On the other hand, there are outstanding research results on optimal or near optimal multiuser resource allocation. In this section, eight major research results for OFDMA systems will be presented.

In [89], the efficient resource allocations for weighted sum rate maximization (WSRmax) and weighted sum power minimization (WSPmin) are proposed. While both schemes are optimal resource allocation for downlink OFDMA systems, these optimization requires $\mathcal{O}(NK^N)$ operations, where N is the number of subcarriers and K is the number of users. WSRmax and WSPmin are non-convex problems whose complexity increases exponentially with the number of tones. However, [89] employs the Lagrange dual decomposition method to efficiently solve the optimization problem. Because the duality gap is virtually zero with a practical number of subcarriers, the Lagrange dual decomposition method can be used to find the optimal solution accurately with a reduced complexity, $\mathcal{O}(NK)$ for WSRmax and $\mathcal{O}(NK^3)$ for WSPmin. The main contribution of [89] is that the proposed approach reduces complexity to be a practical level.

[90] investigates joint subcarrier, power, and rate allocation in OFDMA systems to maximize ergodic rates using WSRmax. This paper derives a convex formulation and an optimal scheduling policy through a time-sharing argument, which can afford a linear complexity, $\mathcal{O}(NK)$. Additionally, [90] introduces on-line scheduling through stochastic approximation iteration, which is capable of dynamically learning the intended channel statistics and asymptotically converging to the off-line optimal solution regardless of the initial condition. [90] shows that an optimal scheduling algorithm can be simply devised for OFDMA uplink operations by changing the sum-power constraint to individual constraints.

[56] presents a unified algorithmic framework for WSRmax resource allocation. This paper formulates both continuous and discrete ergodic WSRmax in OFDMA systems based on a dual optimization framework using perfect CSI. The derived algorithms in [56] require linear complexity, $\mathcal{O}(NK)$, to solve the ergodic rate maximization problem while achieving relative gaps of less than 10^{-4} in practical scenarios. Additionally, this paper shows that ergodic rate maximization is less complex than instantaneous rate maximiza-

tion. Therefore, WSRmax optimizations derived in this paper are effectively applicable in practical situations when ergodic rates are considered.

[91] studies resource allocation algorithms for ergodic continuous and discrete rate maximization in OFDMA systems with imperfect CSI due to estimation errors, as well as channel feedback delay. With the derivation assuming imperfect CSI, [91] shows that the proposed algorithms need a complexity of $\mathcal{O}(NK)$ per iteration and achieves relative duality gaps of less than 10^{-5} for continuous rates and 10^{-3} for discrete rates in typical scenarios. The main contribution of this paper is that it presents an analytical framework for the partial CSI case whose derivations and complexity issues are significantly different from the perfect CSI case. Approximated closed-forms for the performance evaluation in this paper give insight to the effect of imperfect CSI in resource allocation for OFDMA systems.

In [92], a well-known and popular contention based 'opportunistic splitting algorithm' was proposed. The main idea of opportunistic splitting is to divide the time frame into equal sized time slots. The time slots are then classified according to two main goals. The first is to get feedback from individual users, as each time slot is made up of several mini slots allocated to users for feedback. The remaining time slots are used for data transmission to the selected user. In the proposed opportunistic splitting algorithm, all users send their feedback during a mini slot if their current SNR is between the pair of thresholds that all users maintain. When collision among users occurs, the thresholds are modified based on the number of users that competed during a mini slot. This procedure is repeated until only one user contends for feedback during a mini slot. [92] shows that 2.5 mini slots are necessary to find the user, on average. Additionally, this paper shows that the proposed scheme achieves higher capacity with the channel with memory. The contribution of this paper is that the proposed contention based opportunistic splitting algorithm achieves sub-optimal capacity with relatively small feedback and mini slots.

[93] proposed a random access based feedback protocol for clustered OFDM down link. The proposed scheme allows users to feed channel information back to the base station (BS) in a distributed fashion. While opportunistic splitting requires two way communication between the BS and users on every mini slot, the scheme proposed in [93] necessitates only one way communication. In this scheme, active users send a feedback message with some probability if the average channel quality on one cluster is above a specific threshold. The threshold and feedback probability are optimized to maximize the overall sum throughput. If any user is not identified during contention period, the BS randomly selects one user to transmit data. Although the achievable throughput of this model is less than the opportunistic splitting algorithm, the main advantage of [93] is that it exploits multiuser diversity with reduced feedback overhead.

For the best effort traffic, [94] proposed a simple contention-based feedback reducing technique, *static splitting*, that requires only one-way communication as in [93]. In static splitting, users are split into 'static' groups in order to reduce the probability of collision and subsequently achieves a higher system throughput. Unlike previous contention-based opportunistic feedback schemes that commonly use the SNR level to decide threshold values, the proposed scheme in [94] combines static splitting with maximum quantile (MQ) scheduling. The main idea is to schedule the user whose current rate is highest relative to its own distribution. The simulation results show that MQ scheduling maximizes the sum throughput asymptotically in the number of user and is robust to measurement errors compared to conventional SNR scheduling. The other contribution of this paper is that the authors developed a feedback reduction scheme for a mixture of best effort and real-time traffic. The proposed joint polling and opportunistic scheduling (JPOS) is a combination of a token-based scheduling and MQ scheduling. By using JPOS, the proposed scheme can provide Quality of Service (QoS), as well as reduce feedback overhead.

In [95], two constant complexity resource allocation schemes using opportunistic feedback over downlink OFDMA networks was proposed. One scheme uses contention-based opportunistic feedback as previously explained in [92–94], while the other scheme uses subsequential feedback that contains information if the gain of each subcarrier lies within the pair of thresholds. The former reduces feedback overhead to $\mathcal{O}(M \log K)$, while the latter requires more feedback overhead, $\mathcal{O}(M \log M \log K)$, because of the M length bit vector consisting of zeros and ones corresponding to the M tones. An optimal WSRmax problem requires $\mathcal{O}(KMB_{real})$ of feedback overhead to achieve the optimal capacity, where B_{real} is the required bits for quantizing a channel gain. Additionally, the complexity of the proposed scheme is constant, depending on number of iterations at the BS to find the optimal value of λ in the Lagrange dual decomposition method, while that of WSRmas requires $\mathcal{O}(MK)$. Simulation results show that the proposed schemes reduce feedback overhead while achieving a smaller Sum-Rate compared to the optimal WSRmax. Thus, the tradeoff between feedback overhead and the Sum-Rate needs to be carefully considered for this approach.

2.3 System Model

2.3.1 The Conventional Power Allocation for Clustered OFDMA Systems

The analysis begins with a simple model of the downlink of a clustered multiuser OFDM system, where a base station (BS) supports multiple users. In a clustered multiuser OFDM system, the subcarriers are divided into several clusters and each cluster is allocated to a user by opportunistic scheduling. Let the total subcarriers in a multiuser OFDM system be N and the cluster size be N_c. Then, there exist $\lfloor N/N_c \rfloor$ clusters consisting of N_c subcarriers.

The received OFDM symbol of the i^{th} cluster for the k^{th} user is given by $\mathbf{y}_{i,k} = [y_{N_c(i-1)+1,k} \; y_{N_c(i-1)+2,k} \; \cdots \; y_{N_c i,k}]$, where each component of $\mathbf{y}_{i,k}$ can be expressed as

$$y_{n,k} = h_{n,k}\sqrt{p_n}s_{n,k} + z_{n,k}, \quad N_c(i-1)+1 \leq n \leq N_c i \tag{2.1}$$

where $h_{n,k}$ is an independently and identically distributed (i.i.d.) complex Gaussian channel gain [96], p_n is the power allocated to the n^{th} subcarrier, $s_{n,k}$ is the transmitted data symbol, and $z_{n,k}$ is an i.i.d Gaussian noise with mean zero and variance σ^2 for the n^{th} subcarrier. The channel is assumed to be static during a coherence time T_c, $|s_{n,k}|^2 = 1$, and inter-symbol interference (ISI) is perfectly eliminated through a cyclic prefix. Then, the received SNR (preprocessing SNR) of the n^{th} subcarrier for the k^{th} user is obtained by

$$SNR_{n,k} = \frac{|h_{n,k}|^2 p_n}{\sigma^2}. \tag{2.2}$$

Correspondingly, the maximum achievable data rate for the i^{th} cluster is given by

$$R_i = \arg \max_{k \in 1 \cdots K} \sum_{n=N_c(i-1)+1}^{N_c i} \left[\frac{B}{N_c} \log_2 \left(1 + \frac{|h_{n,k}|^2 p_n}{\sigma^2} \right) \right] \text{bps}, \tag{2.3}$$

where B is the bandwidth of a cluster consisting of N_c subcarriers.

Under opportunistic user scheduling, each user feeds back quantized information of the achievable rate for each subcarrier cluster. Then, the home BS assigns each subcarrier cluster to a user with the best achievable rate to achieve multiuser diversity gain. From a practical viewpoint, the cluster allocation can be done periodically on the order of a channel coherence time or training.

2.3.2 Random Waterfilling Power Allocation

As previously mentioned, the throughput difference between optimal waterfilling and equal power allocation grows as the SNR diminishes [87]. In this context, a new random waterfilling power allocation is proposed that is applicable to clustered multiuser OFDM systems. In random waterfilling power allocation, the total transmit power P is equally divided into $\lfloor N/N_c \rfloor$ clusters,

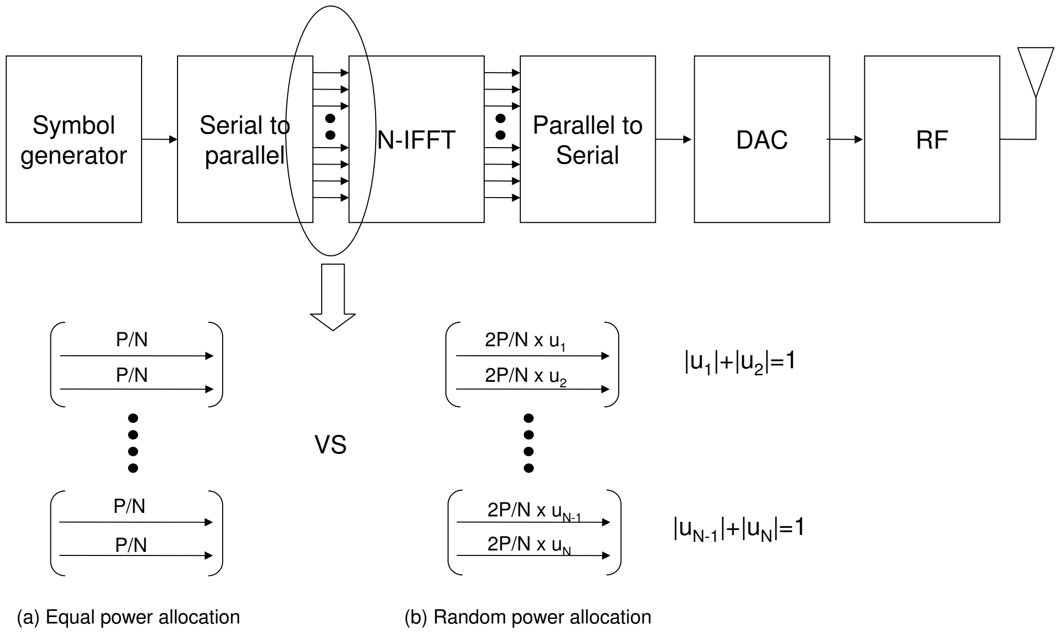

Figure 2.2: Equal power allocation vs. random power allocation

and then the power for a cluster, $P_c = P/\lfloor N/N_c \rfloor$ is randomly allocated to subcarriers in a cluster. Fig. 2.2 (b) is an example when the cluster size is two. In this case, the power allocated to each subcarrier for the first cluster are $u_1 \cdot 2P/N$ and $u_2 \cdot 2P/N$, respectively, where u_1 and u_2 are random numbers between 0 and 1 and satisfies $|u_1| + |u_2| = 1$. Then, each cluster is assigned to the user with the highest achievable data rate. Correspondingly, the achievable data rate of the first cluster is given by

$$R_1 = \max_{k \in 1 \cdots K} \left[\frac{B}{N_c} \left[\log_2 \left(1 + \frac{|\sqrt{u_1} h_{1,k}|^2 P_c}{\sigma^2} \right) + \log_2 \left(1 + \frac{|\sqrt{u_2} h_{2,k}|^2 P_c}{\sigma^2} \right) \right] \right] \text{bps/Hz}. \tag{2.4}$$

Compared to conventional waterfilling systems, where u_1 and u_2 are obtained with the exact channel state information under a given power constraint, the proposed random waterfilling takes advantage of conventional waterfilling without the exact channel state information at the transmitter. In other words, if there is a sufficiently large number of users, the possibility that the randomly generated power coefficients, u_1 and u_2, match to the exact waterfilling power configuration significantly increases because each user's channel is faded independently. Eventually, multiuser diversity is efficiently amplified from random power generation.

2.4 Throughput Analysis under Opportunistic User Scheduling

2.4.1 Conventional Clustered OFDMA Systems with Equal Power Allocation

Under opportunistic scheduling, the i^{th} cluster is assigned to the user satisfying

$$\arg\max_{k\in 1\cdots K} \sum_{n=N_c(i-1)+1}^{N_c i} \log_2\left(1+\frac{|h_{n,k}|^2 P}{N\sigma^2}\right) \tag{2.5}$$

where P is the total transmit power, and, correspondingly, the total power allocated to one cluster, P_c is $P/\lfloor N/N_c \rfloor$. Fig.2.2 (a) shows the concept of equal power allocation in an multiuser OFDM system with cluster size $N_c = 2$. The sum capacity is then obtained by

$$C = \sum_{i=1}^{\lfloor N/N_c \rfloor} \max_{k\in 1\cdots K} \sum_{n=N_c(i-1)+1}^{N_c i} \left[\frac{B}{N_c} log_2\left(1+\frac{|h_{n,k}|^2 P}{N\sigma^2}\right)\right] \text{bps.} \tag{2.6}$$

where B is the bandwidth of a cluster consisting of N_c subcarriers.

2.4.2 OFDMA System with the Proposed Random Waterfilling

Since each cluster is assigned to the best user after random power allocation, the sum capacity of a clustered multiuser OFDM system is obtained by

$$C = \sum_{i=1}^{\lfloor N/N_c \rfloor} \max_{k \in 1 \cdots K} \sum_{n=N_c(i-1)+1}^{N_c i} \left[\frac{B}{N_c} \log_2 \left(1 + \frac{|\sqrt{u_n} h_{n,k}|^2 |P_c|}{\sigma^2} \right) \right] \text{bps} \tag{2.7}$$

and the ergodic capacity can be obtained after averaging (2.7) over fading channel realizations by

$$C_{avg} = \left\lfloor \frac{N}{N_c} \right\rfloor \mathbb{E}\left[R_{1,k}\right] \text{bps}, \tag{2.8}$$

where $R_{1,k}$ is the achievable data rate of the first cluster, given by

$$R_{1,k} = \max_{k \in 1 \cdots K} \sum_{n=1}^{N_c} \frac{B}{N_c} \log_2 \left(1 + \frac{|\sqrt{u_n} h_{n,k}|^2 |P_c|}{\sigma^2} \right). \tag{2.9}$$

Because it is difficult to derive a closed form of C_{avg}, numerical integration or a Monte Carlos simulation can be used to find C_{avg}. However, an upper bound on the ergodic capacity can be derived using order statistics [97] [98]. The analytical upper bound can explicitly explain how the ergodic capacity increases with the number of users. For analytical simplicity, system with cluster size $N_c = 2$ is considered. Then, $R_{1,k}$ is given by

$$R_{1,k} = \frac{B}{2} \max_{k \in 1 \cdots K} \log_2 S_{1,k}. \tag{2.10}$$

where

$$S_{1,k} = 1 + \frac{|\sqrt{u_1} h_{1,k}|^2 |P_c|}{\sigma^2} + \frac{|\sqrt{u_2} h_{2,k}|^2 |P_c|}{\sigma^2} + \frac{|\sqrt{u_1} h_{1,k}|^2 |\sqrt{u_2} h_{2,k}|^2 |P_c|^2}{\sigma^4}. \tag{2.11}$$

Then, the ergodic capacity is given by

$$C_{avg} = \left\lfloor \frac{N}{2} \right\rfloor \frac{B}{2} \log_2 \mathbb{E}\left[\max_{k \in 1 \cdots K} S_{1,k}\right] \text{bps}, \tag{2.12}$$

where it should be noted that the expectation $\mathbb{E}[\cdot]$ can move into $\log_2(\cdot)$ since a log function is a monotonically increasing function. Using order statistics, an upper bound on $\mathbb{E}\left[\max_{k \in 1 \cdots K} S_{1,k}\right]$ is obtained by

$$\mathbb{E}\left[\max_{k \in 1 \cdots K} S_{1,k}\right] \leq \mathbb{E}[S_{1,k}] + \frac{K-1}{\sqrt{2K-1}} \sqrt{\mathrm{Var}[S_{1,k}]}. \tag{2.13}$$

where

$$\mathbb{E}\left[S_{1,k}\right] = \int_0^\infty \int_0^\infty \int_0^1 S_{1,k} \cdot \exp(-x)\exp(-y)\mathrm{dudxdy} \tag{2.14}$$

and

$$\mathrm{Var}\left[S_{1,k}\right] = \int_0^\infty \int_0^\infty \int_0^1 S_{1,k}^2 \cdot \exp(-x)\exp(-y)\mathrm{dudxdy} - \mathbb{E}\left[\mathrm{S_{1,k}}\right]^2. \tag{2.15}$$

where $x = h_{1,k}^2$, $y = h_{2,k}^2$, and $u = u_1$ respectively.

Then, an upper bound on C_{avg} is derived as

$$C_{avg} \leq \left\lfloor \frac{N}{2} \right\rfloor \frac{B}{2} \cdot \log_2 \left(\mathbb{E}[S_{1,k}] + \frac{K-1}{\sqrt{2K-1}} \sqrt{\mathrm{Var}[S_{1,k}]} \right) \text{bps}. \tag{2.16}$$

From the derived upper bound on the ergodic capacity, it can be found that the ergodic capacity of the clustered multiuser OFDM system with the proposed random waterfilling grows like $\mathcal{O}\left(\log_2 \sqrt{\frac{K}{2} - 1}\right)$ regardless of the cluster size, because the cluster size affects the mean and variance of $S_{1,k}$ in (2.16).

2.4.3 Weighted Sum Rate Maximization (WSRmax)

As previously explained in Section 2.2, the optimal DL OFDMA resource allocation is WSRmax [56, 89–91]. Although the goal of this research is only focused on the performance enhancement of the clustered OFDMA systems with equal power allocation without an increase of complexity and feedback, the performance of WSRmax can be provided for the optimal upper bound. WSRmax is briefly summarized in this context.

If we consider a full CSI environment, the achievable capacity of user k on subcarrier n is obtained by

$$r_{n,k} = \log_2 (1 + p_{n,k}\gamma_{n,k}) \tag{2.17}$$

where $\gamma_{n,k} = |h_{n,k}|^2/\sigma^2$ and $p_{n,k}$ is power allocated to user k on subcarrier n.

Let $\mathcal{K}_k$ denote the set of subcarriers allocated user k. Since each subcarrier is allowed to be allocated by at most one user, $\mathcal{K}_i \cap \mathcal{K}_j = \varnothing$ for $i \neq j$ and $\bigcup_{k=1}^{K} \mathcal{K}_k \subset \{1, 2, \cdots, N\}$. Then, the WSRmax problem is formulated by

$$\begin{aligned} f^* &= \max \sum_{k=1}^{K} w_k \sum_{n \in \mathcal{K}_k} r_{n,k} \\ \text{subject to} & \qquad \sum_{k=1}^{K} \sum_{n \in \mathcal{K}_k} p_{n,k} \leq P \end{aligned} \tag{2.18}$$

where $p_{n,k} \geq 0$ for $\forall k$ and $\forall n$, w_k is weight assigned to user k. Subsequently, the dual problem can be derived by

$$\begin{aligned} g^* &= \min \left[\lambda P + \max \left\{ \sum_{k=1}^{K} w_k \sum_{n \in \mathcal{K}_k} \log_2 (1 + p_{n,k}(\lambda)\gamma_{k,n}) - \lambda p_{n,k}(\lambda) \right\} \right] \\ \text{subject to} & \qquad \lambda \geq 0 \end{aligned} \tag{2.19}$$

where $p_{n,k}(\lambda)$ is the optimal powers given by

$$p_{m,k}(\lambda) = \left[\frac{1}{\gamma_{0,k}} - \frac{1}{\gamma_{n,k}}\right]^{+} \tag{2.20}$$

where $[f(x)]^{+} = \max(0, f(x))$ and $\gamma_{0,k}(\lambda) = \lambda \ln 2/w_k$. This power allocation is eventually *multi level water-filling* with cut off SNR $\gamma_{0,k}(\lambda)$. Because the duality gap is known to be near zero for a practical number of subcarriers, the optimal power and subcarrier allocation are obtained by Lagrange dual decomposition.

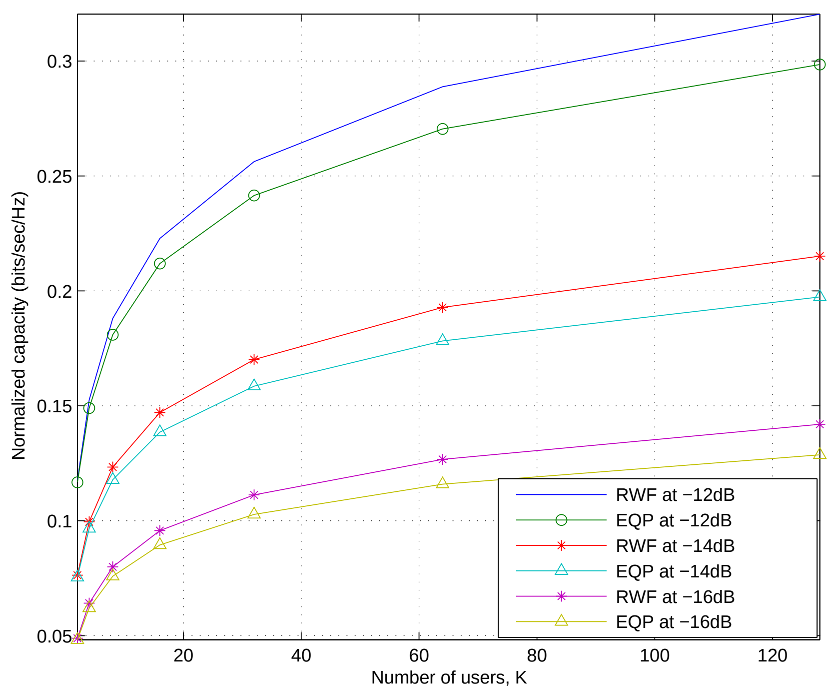

Figure 2.3: The capacity comparison with different SNR. The capacity difference between random waterfilling (RWF) and equal power (EQP) scheme increases as the SNR decreases

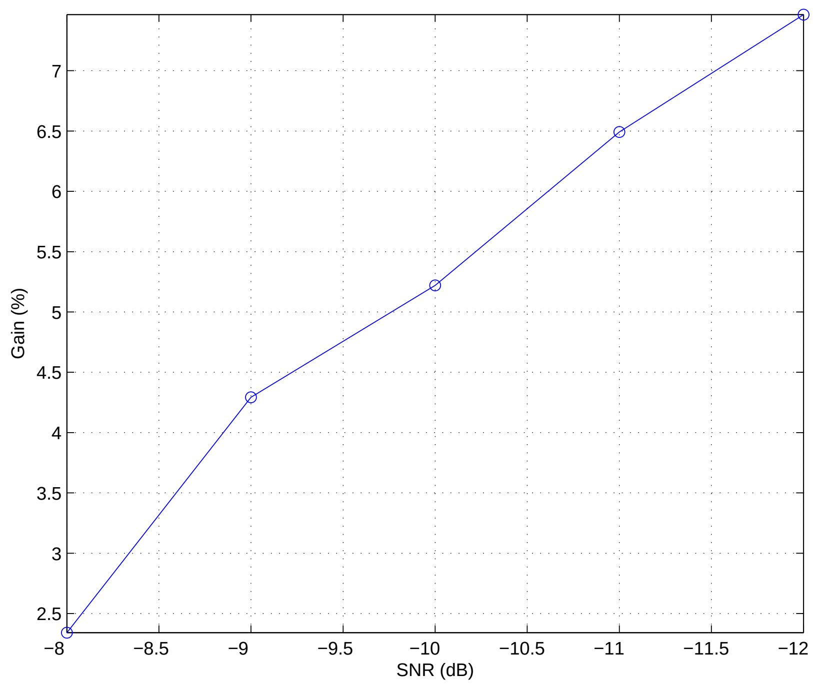

Figure 2.4: The gain with different SNR. The proposed scheme becomes more efficient as SNR decreases.

2.5 Numerical Results

In this section, random waterfilling is analyzed using numerical results. An OFDM symbol duration is assumed to be $100.8\mu s$, which corresponds to IEEE 802.16 WirelessMAN [11]. Also users with 3 km/hr mobility are considered so that the coherence time equals 43.5 msec when the center frequency is 3.6 GHz.

The comparison of normalized capacity for each scheme is shown in Fig. 2.3. In this figure, it can be verified that the proposed random waterfilling has

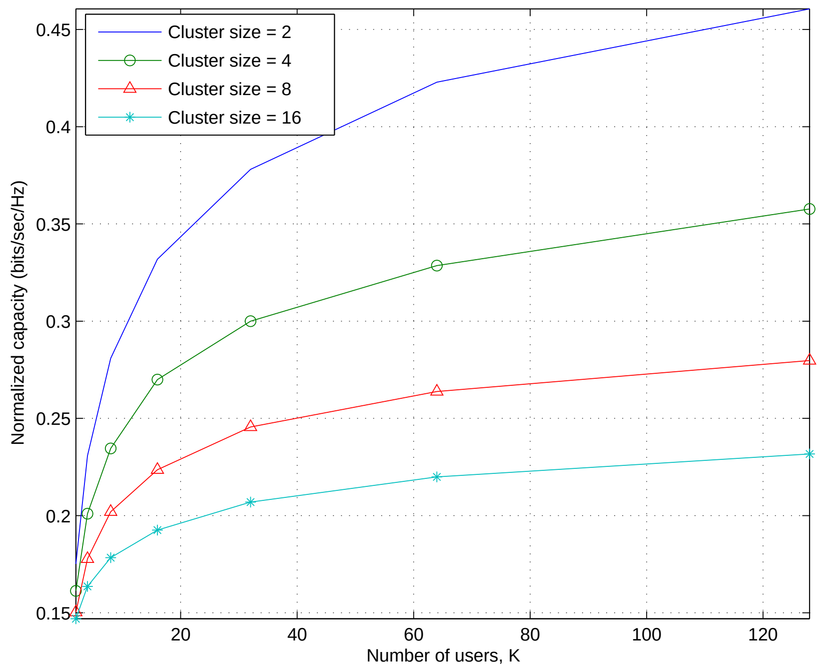

Figure 2.5: The normalized capacity with different cluster sizes at -10 dB when random waterfilling is used. The throughput gain decreases as the size of cluster becomes larger.

an advantage over the conventional equal power allocation in the very low SNR regime. Additionally, the capacity gain over equal power allocation for various received SNR levels is presented in Fig. 2.4. This figure suggests that the random waterfilling algorithm can be more effectively used when the received SNR decreases. This capacity gain comes from the better efficiency of the waterfilling algorithm in the lower SNR regime. Since the power configuration of random waterfilling approaches to that of the optimal waterfilling for a large number of users, the capacity gain over conventional equal power allocation increases as the number of users are increased. Therefore, the proposed random waterfilling scheme can be effectively adopted to the overlaid systems operating in the very low SNR regime.

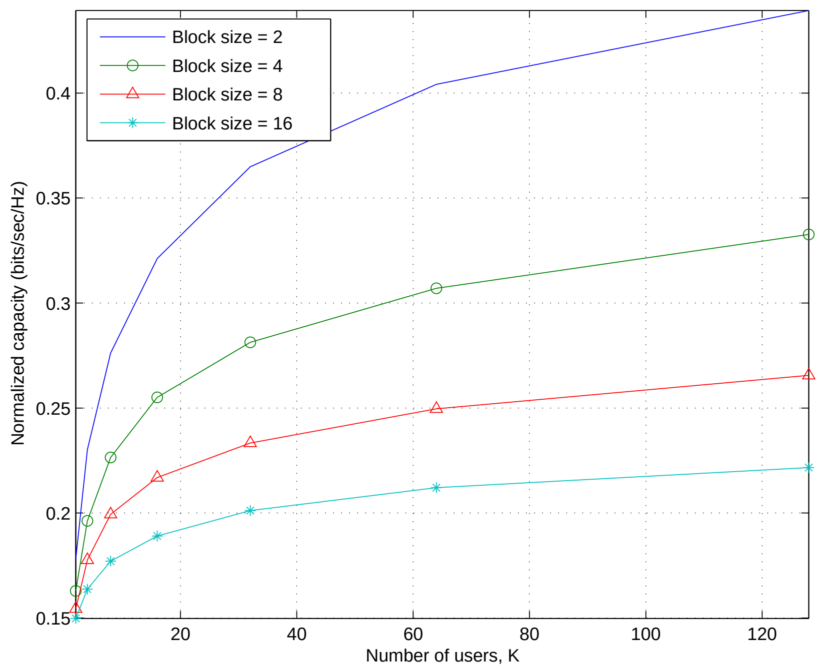

Figure 2.6: The normalized capacity with different cluster sizes at -10 dB when equal power allocation is used. The throughput gain decreases as the size of cluster becomes larger.

Fig. 2.5 compares the normalized capacity, which is the same as the spectral efficiency, for different cluster sizes. Interestingly, it is observed that normalized capacity decreases with cluster size when using the random waterfilling power allocation due to the increased dimension. As the cluster size becomes larger, the dimension, the number of subcarriers in this case, for

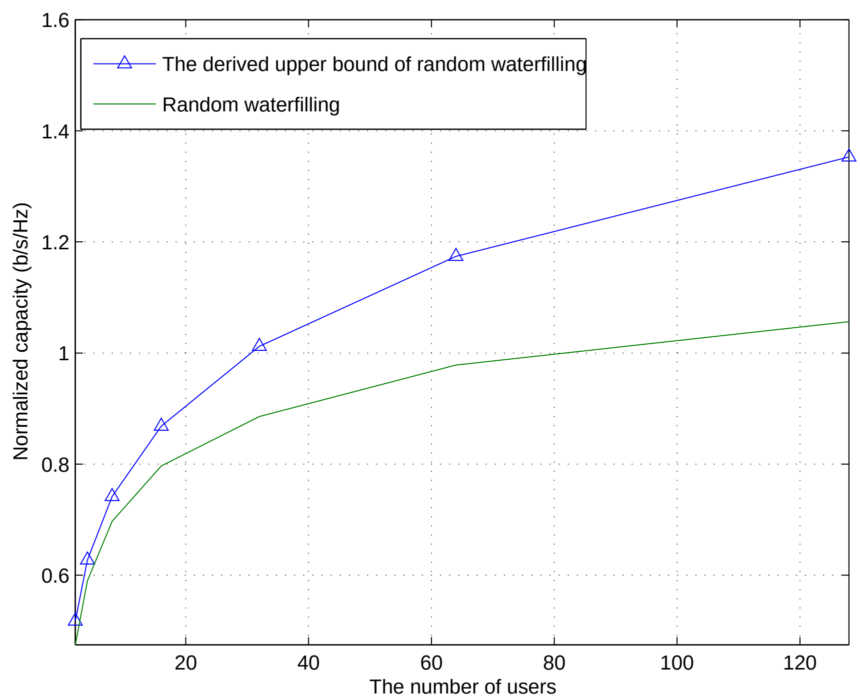

Figure 2.7: The derived upper bound of random waterfilling at -5 dB.

the waterfilling algorithm grows proportionally. Since this increase in dimension reduces the probability that random power allocation becomes similar to the optimal waterfilling configuration, it is obvious that the sum capacity is decreased as the cluster size is increased. The same inefficiency from the increased dimension is also found in the conventional opportunistic multiuser OFDM systems as shown in Fig. 2.6.

The analytic upper bound on the normalized capacity of the proposed random waterfilling is shown in Fig. 2.7, which was derived in (2.16). Although the analytical upper bound is not tight, it can be verified that the

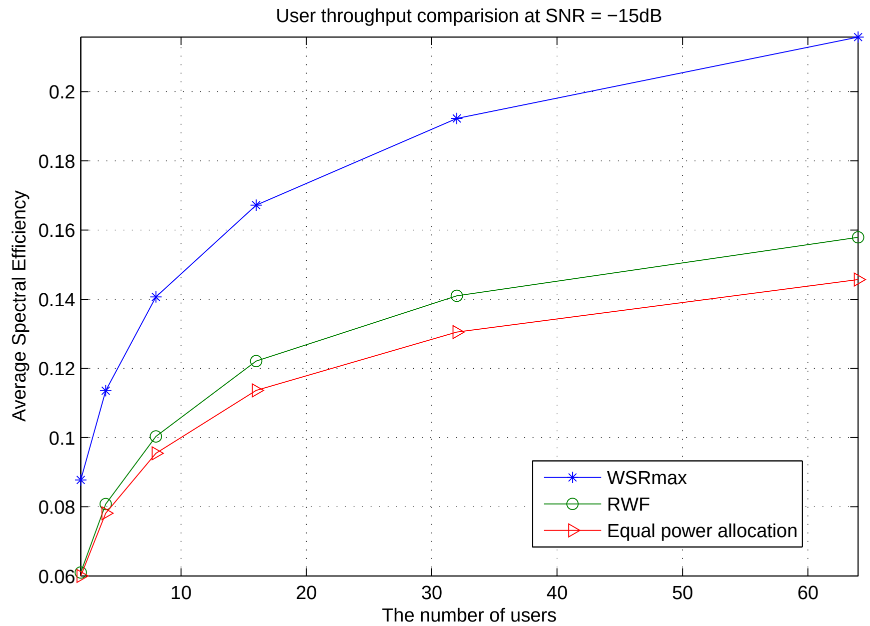

Figure 2.8: Capacity using WSRmax is the upper bound of the capacity.

capacity grows like $\mathcal{O}\left(\log_2 \sqrt{\frac{K}{2}-1}\right)$ Furthermore, the derived approach can be applied to the conventional opportunistic multiuser OFDM systems. Although their upper bounds are different from that of the proposed random waterfilling due to the different mean and variance given in (2.14) and (2.15), it is easy to estimate that the conventional opportunistic multiuser OFDM systems also grow like $\mathcal{O}\left(\log_2 \sqrt{\frac{K}{2}-1}\right)$ from (2.16).

Finally, Fig. 2.8 compares the capacity of the proposed scheme with that of WSRmax resource allocation and conventional equal power allocation with opportunistic scheduling. Equal weights are assumed for the opportunistic user selection. It is obvious that WSRmax achieves the optimal capacity and is more efficient as operating SNR range decreases. While the WSR-max achieves the upper bound of capacity, it requires full or partial CSI of all subcarriers, as well as iterative procedures to obtain multi level waterfill power allocations. Although WSRmax is the optimal resource allocation for DL OFDMA systems, open loop power control is still required for the systems with a more limited feedback and lower complexity requirement, or in a very fast fading environment [26, 27]. Therefore, although Random Waterfilling achieves smaller capacity compared to WSRmax, a meaningful performance enhancement over conventional open loop power control is achieved without an increase of feedback or complexity by Random Waterfilling as shown in Fig. 2.8.

2.6 Conclusions

In this chapter, a new random waterfilling power allocation applicable to clustered multiuser OFDM systems operating in the low SNR regime has been proposed. The proposed random waterfilling effectively amplifies the multiuser diversity gain in perspective of power allocation so that a meaningful capacity gain over conventional equal power allocation is achieved in the low SNR regime. This chapter also provides the upper bound on the sum capacity for the proposed random waterfilling, which explains how the sum capacity increases with the number of users. The proposed random waterfilling algorithm is effective in the very low SNR regime compared to equal power allocation.

Chapter 3

Modified Multi-mode Power Loading Scheme for Large Dimensional OFDM Systems

3.1 Background and Prior Work

Adaptive power loading techniques according to the channel variations are able to enhance the capability of OFDM systems [62, 99]. Specifically, OFDM systems using distributed subcarriers, such as precoded OFDM systems [100] or distributed mode in 3 GPP LTE [12], require adaptive power loading to efficiently improve achievable capacity. However, in general they require a large amount of feedback information and other overhead for the link adaptation.

Several techniques have been studied for adaptive power loading with limited feedback. Power loading using threshold value was proposed in [75], where water-filling and on-off power configurations are decided for the subcarrier whose channel gain is over threshold value. In [101], the performance of subcarrier allocation, power allocation, and rate loading with one bit feedback per subcarrier is analyzed. The paper [102] studies the minimum feedback rate required to specify the sequence of active subchannels for on-off power configuration. The performance analysis of one-bit channel feedback with perfect and imperfect feedback channel knowledge is presented in [31]. Among many techniques, the multi-mode power loading technique [53] is attractive since it avoids iterative procedures and periodic updates of a threshold value in order to find the best power loading configuration. Multi-mode power loading is a power loading algorithm based on the on-off configurations of subcarriers, where the transmitter equally allocates its available power only to the subcarriers indicated as "on". In multi-mode power loading, the transmitter and receiver share a codebook containing all possible on-off configurations of the subcarriers, and the receiver selects a codeword maximizing capacity by a brute-force search of the whole codebook. By only feeding the index of the selected codeword back to the transmitter, the multi-mode power loading is able to limit the required feedback bits to N bits for power loading, where N is the total number of subcarriers. However, this technique's critical drawback is that the complexity of brute-force searches over the codebook grows exponentially with N so that multi-mode power loading becomes impractical for large N. Research has shown that multi-mode power loading is plausible only when N is around 10 considering the complexity of the brute-force searches [53].

In this context, a new power loading technique is proposed to generate the same optimal power loading configuration as the multi-mode power loading technique without recourse to brute-force searches [103]. The proposed technique requires only N searches while the multi-mode power loading necessitates $2^N - 1$ brute-force searches. Thus, the method works well with large N on a practical level. The required feedback amount of the proposed technique is the same as the multi-mode power loading: N bits. In addition, the proposed technique does not need a shared codebook, so it is able to save the memory space for the codebook at the transceiver.

3.2 System Model

This section begins with a simple model of the downlink of N tone (or N subcarrier) OFDM system. If perfect pulse shaping, sampling, synchronization, and phase recovery are assumed, the received OFDM symbol at a given symbol time can be described as $\mathbf{y} = [y_1 \ y_2 \ \cdots \ y_N]$. The i^{th} component of $\mathbf{y}$, y_i is given by

$$y_i = h_i x_i + z_i \tag{3.1}$$

where h_i is an independent and identically distributed (i.i.d.) complex Gaussian channel gain [96], x_i is the transmitted signal, and z_i is an i.i.d Gaussian noise with mean zero and variance σ^2 for the i^{th} subcarrier. The channel gain h_i is assumed to be static during a symbol duration. The frequency domain input-output expression from (3.1) can be collected in vector form as

$$\mathbf{y} = \mathbf{H}\mathbf{x} + \mathbf{n} \tag{3.2}$$

where $\mathbf{y} = [y_1 \ y_2 \ \cdots \ y_N]^T$, $\mathbf{H} = diag(h_1, h_2, \cdots, h_N)$, $\mathbf{x} = [x_1 \ x_2 \ \cdots \ x_N]^T$, and $\mathbf{n} = [n_1 \ n_2 \ \cdots \ n_N]^T$. It is assumed that $\mathbb{E}[n_i^* n_j] = 0$ when i$\neq$ j. In this chapter, $\mathbf{h}$ will be used to refer to $[h_1 \ h_2 \ \cdots \ h_N]^T$

In adaptive power allocation, x_i can be given by

$$x_i = \sqrt{p_i} s_i \tag{3.3}$$

where p_i is the allocated power to i^{th} subcarrier and s_i is the transmitted data symbol. Then, total power constraint is given by

$$\sum_{i=1}^{N} p_i = P. \tag{3.4}$$

Also it is assumed that capacity is independent of the phase and $|s_i|^2 = 1$ on each subcarrier.

3.2.1 Multi-mode Power Loading

The key ideas of multi-mode power loading [53] can be used to derive the proposed power loading technique. Let $\mathcal{S}$ be the set of all non-empty subsets of $\{1, 2, 3, \cdots, N\}$. Then the vector space $\mathcal{A}$ consisting of $2^N - 1$ vectors $\mathbf{p}_i$ is defined by

$$\mathcal{A} = \{\mathbf{p}_1, \mathbf{p}_2, \cdots, \mathbf{p}_{2^N-1}\} = \left\{ \frac{1}{\text{card}(\mathcal{I})} \sum_{i \in \mathcal{I}} \mathbf{e}_i \mid \forall \mathcal{I} \in S \right\} \tag{3.5}$$

where $\mathbf{e_i}$ is the ith column of the $N \times N$ identity matrix and $\text{card}(\mathcal{I})$ is the cardinality of $\mathcal{I}$.

In multi-mode power loading, the optimal power configuration is selected after brute-force searches over $2^N - 1 \left(= \sum_{k=1}^{N} \binom{N}{k} \right)$ configurations of subcarriers to maximize the achievable capacity such that

$$\mathbf{p}_{opt} = \arg\max_{\mathbf{p} \in \mathcal{A}} C(\mathbf{p}|\mathbf{h}) = \arg\max_{\mathbf{p} \in \mathcal{A}} \frac{1}{N} \sum_{i=1}^{N} \log_2 \left(1 + \frac{p_i |h_i|^2}{\sigma^2} \right). \tag{3.6}$$

where $\mathbf{p}$ is a power loading vector $\mathbf{p} = [p_1 \; p_2 \; \cdots \; p_N]^T$ and the total power constraint is $\sum_{i=1}^{N} p_i = P = 1$. As mentioned in the Introduction, the brute-force searches of $2^N - 1$ candidates makes the multi-mode power loading infeasible as N grows.

By dividing the vector space $\mathcal{A}$ into N subspaces given by

$$\mathcal{A}_k = \left\{ \frac{1}{\mathrm{card}(\mathfrak{I})} \sum_{i \in \mathfrak{I}} \mathbf{e}_i \mid \forall \mathfrak{I} \in S,\ \mathrm{card}(\mathfrak{I}) = k \right\} \tag{3.7}$$

where $k \in \{1, 2, \cdots, N\}$, the optimal power configuration after brute-force searches given in (3.6) can be alternatively expressed by the following two steps:

$$\mathbf{p}_{opt,k} = \arg\max_{\mathbf{p} \in \mathcal{A}_k} C_k(\mathbf{p}|\mathbf{h}) = \arg\max_{\mathbf{p} \in \mathcal{A}_k} \frac{1}{N} \sum_{i=1}^{N} \log_2 \left(1 + \frac{p_i |h_i|^2}{\sigma^2} \right),\ \ k = 1, \cdots, N. \tag{3.8}$$

$$\mathbf{p}_{opt} = \underset{\mathbf{p}_{opt,k}, k=1,\cdots,N}{\mathrm{argmax}} C_{k,max}(\mathbf{p}_{opt,k}|\mathbf{h}) = \underset{\mathbf{p}_{opt,k}, k=1,\cdots,N}{\mathrm{argmax}} \frac{1}{N} \sum_{i=1}^{N} \log_2 \left(1 + \frac{p_i |h_i|^2}{\sigma^2} \right) \tag{3.9}$$

3.2.2 The Proposed Power Loading Technique

The proposed power loading technique is motivated by the alternative expressions given in (3.8) and (3.9). For a given k, the optimal power loading vector $\mathbf{p}_{opt,k}$ in (3.8) has k non-zero elements with the value of $1/k$. According to multi-mode power loading, the optimal indices of non-zero elements of $\mathbf{p}_{opt,k}$ are to be found through brute-force searches of $\binom{N}{k}$ candidates.

Instead of the brute-force searches, the proposed technique exploits the strictly increasing property of a log function. For a given k, the capacity $C_k(\mathbf{p}|\mathbf{h})$ is maximized when the indices of non-zero elements of $\mathbf{p}$ equal to the indices of the k highest elements of $\mathbf{h}$ since the function $\log_2(\cdot)$ is strictly increasing. Correspondingly the maximum achievable capacity for a given k is given by

$$C_{k,max} = C(\mathbf{p}_{opt,k}|\mathbf{h}) = \frac{1}{N}\sum_{i=1}^{k}\log_2\left(1+\frac{|\tilde{h}_i|^2}{k\sigma^2}\right) = \frac{1}{N}\sum_{i=1}^{k}\log_2\left(1+\frac{|h_{g(i)}|^2}{k\sigma^2}\right) \tag{3.10}$$

where $\tilde{\mathbf{h}}$ is the vector representing the sorted channel gains and given by

$$\tilde{\mathbf{h}} = [\tilde{h}_1 \ \cdots \ \tilde{h}_N] = [h_{g(1)}, \cdots, h_{g(N)}] \tag{3.11}$$

where $|\tilde{h}_i| > |\tilde{h}_j|$ if $i < j$ and $g(n)$ indicates the index of the nth largest element of $\mathbf{h}$. Therefore, the optimal power loading vector for given k can be easily determined by sorting the channel gains of N subcarriers in a descending order and finding the indices of the k largest channel gains. Let $\mathbf{p}_{opt,k} = [p_1, p_2, \cdots, p_N]$ then its elements are determined by

$$p_i = \begin{cases} \frac{1}{k} & \text{if } i \in \{g(1), g(2), \cdots, g(k)\} \\ 0 & \text{otherwise} \end{cases} \tag{3.12}$$

Finally, $\mathbf{p}_{opt}$ is selected among N candidates $\mathbf{p}_{opt,k},\ k = 1, \cdots, N$ to maximize the capacity as in (3.9). Brute-force searches are not used in the proposed scheme. Instead, the order of channel gains is exploited to find $\mathbf{p}_{opt,k}$ for each k. Therefore, the total required searches to find $\mathbf{p}_{opt}$ is reduced to N while multi-mode power loading requires $2^N - 1$ searches.

Although the idea of sorting subchannel gains, (3.11), was introduced previously in [54], the proposed scheme exploits the sorting in a novel way. [54] proposed 2 efficient greedy loading algorithms that require 5 step procedures:

Grouping $\longrightarrow$ Sorting $\longrightarrow$ Clustering $\longrightarrow$ Equivalent subchannel gains $\longrightarrow$ Greedy loading over clusters. Key idea of efficient greedy loading (EGL) is that logical clusters can be assumed to be in a flat fading by sorting subchannel gains in a group. So sorting is used for clustering subchannels. The complexity for two EGL schemes is proportional with

$$N_{sorting} + (N_{cluster} \times N_{iterations}) + N_{multiplies} + N_{TA} \tag{3.13}$$

where $N_{sorting}$, $N_{cluster}$, $N_{iterations}$, $N_{multiplies}$, and N_{TA} are the number of sorting, clusters, iterations, multiplies, and table access respectively.

On the other hand, the proposed scheme in this chapter uses on-off power loading that does not require iterations. In this approach, sorting has been used for reducing the amount of brute-force search. Previous multimode power loading requires $2^N - 1$ comparison while the proposed scheme necessitates only N (number of comparison) + $N \log_2 N$ (number of sorting).

Eventually, although both EGL and the proposed scheme in this chapter use sorting, their goal and loading approach is quite different (sorting is a part of loading algorithm). In EGL, logical cluster decreases dimensions of greedy loading and sorting makes logical cluster possible. As shown in (3.13), complexity is not dependent on sorting only. In the proposed scheme, sorting makes the required comparison small but is not related with clustering (smaller dimension). Complexity of the proposed scheme is not dependent on sorting only either. Therefore, the contribution of power loading proposed in this chapter is to decrease the number of brute-force search using sorting and to make a bitmap that does not use codebook in conventional multimode power loading.

The proposed technique achieves the same optimal power configuration as multi-tone power loading without brute-force searches and requires the same amount of feedback bits: N bits. Relaxing the requirement of brute-force searches enables the proposed technique to be practically feasible even with large N. The proposed technique works well without a shared codebook so it is able to save the memory space. Fig. 3.1 presents the algorithm of the proposed technique.

3.3 Numerical Analysis

In this section, the proposed technique is compared with multi-mode power loading and waterfilling power loading with full CSIT in terms of the search amount and the achievable capacity.

The averaged spectral efficiency between the proposed scheme and multi-mode power loading is compared in Fig. 3.2. Because multi-mode power loading is impractical for large N as noted in [53], each capacity is compared when $N = 4$. This figure shows that the averaged spectral efficiency of the proposed scheme is exactly the same as the averaged spectral efficiency of multi-mode power loading. From this figure, it can be verified that the proposed scheme can select the same power loading vector as multi-mode power loading with a significantly smaller search amount, as estimated in the previous section.

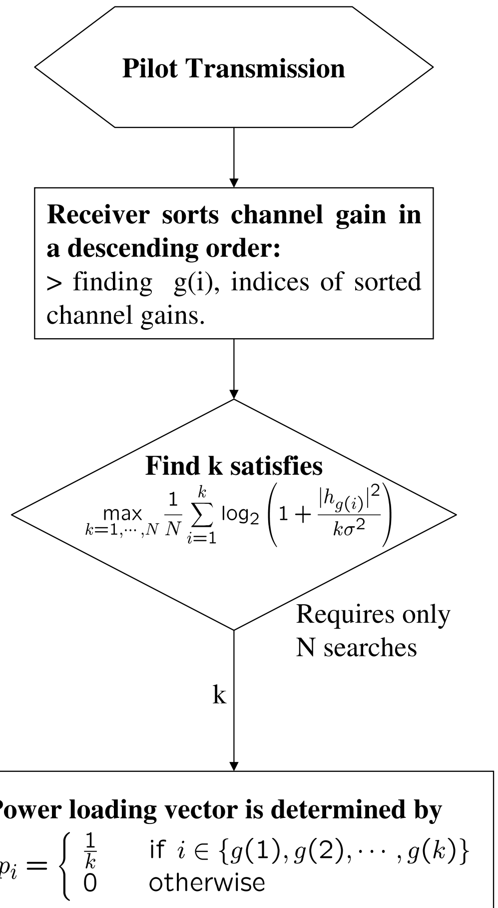

Figure 3.1: The flow chart of the proposed scheme.

The required search amount of the proposed scheme and multi-mode power loading is compared in Fig. 3.3. As previously mentioned, the conventional multi-mode power loading requires $2^N - 1$ searches to find the best power loading configuration while the proposed scheme necessitates only N searches to find the same optimal power loading configuration. The only additional complexity of the proposed technique at the receiver is for a simple

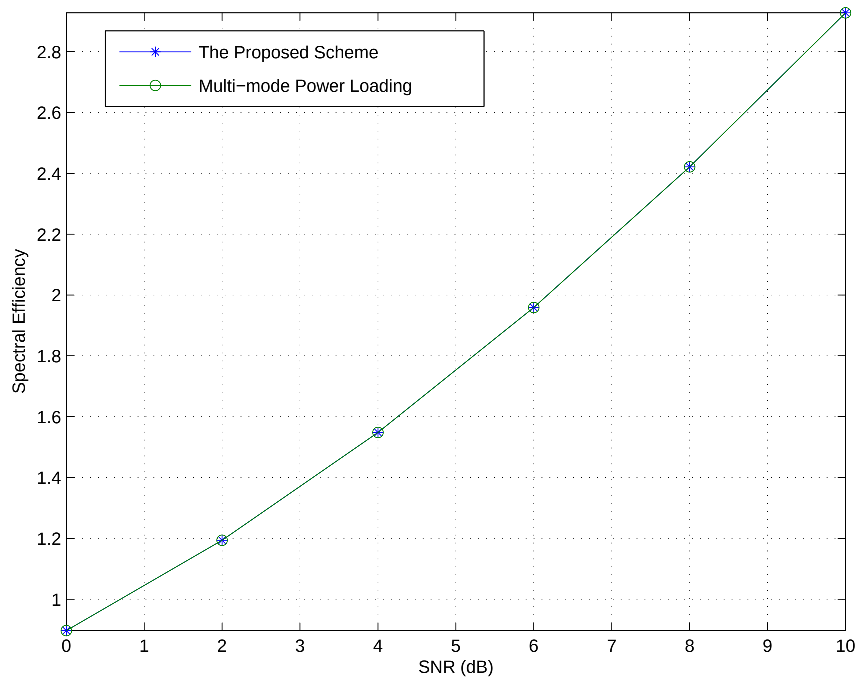

Figure 3.2: Capacity comparison between the proposed scheme and multi-mode power allocation. Both capacities are exactly same as each other.

ordering to find the indices of the k highest channel gains for given k, but this consideration is marginal.

Finally, Fig. 3.4 shows the averaged spectral efficiency of the proposed scheme, multi-mode power loading, waterfilling with full CSIT, and equal power allocation. The capacity difference between the proposed scheme and waterfilling with full CSIT is marginal while the required feedback amount is significantly reduced in the proposed technique. For example, if it is assumed that B bits are required for feedback of one subcarrier channel gain, full CSIT

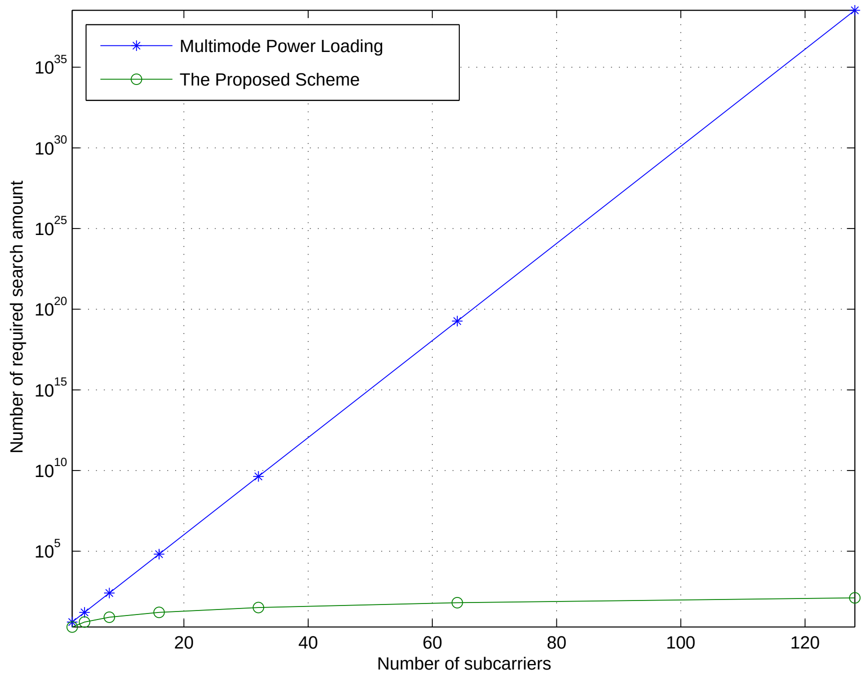

Figure 3.3: Search amount comparison between the proposed scheme and multi-mode power allocation. The proposed scheme can reduce search amount significantly.

necessitates BN bits while the proposed scheme and multi-mode power loading only need N bits for feedback.

3.4 Conclusions

This chapter has proposed a new power loading technique circumventing the limits of multi-mode power loading while maintaining the advantages of multi-mode power loading. The proposed technique reduces the required search amount to N while multi-mode power loading must perform $2^N - 1$

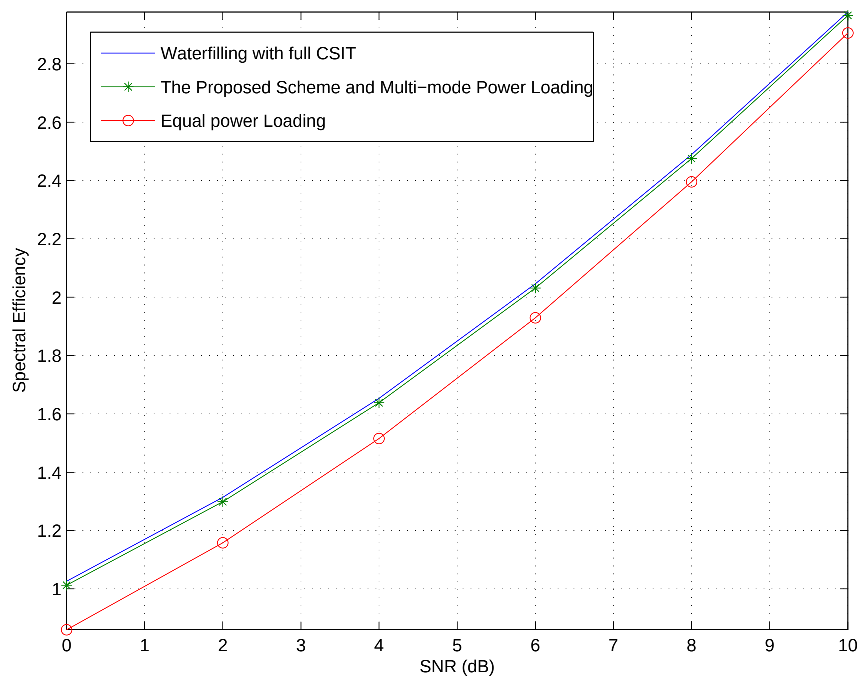

Figure 3.4: Spectral efficiency of various power loading techniques. Capacity loss of the proposed scheme is marginal compared to the capacity of the optimal power loading.

brute-force searches to find the best power configuration. As a result, the proposed technique works well even for large N whereas multi-mode power loading does not. Through the analysis and numerical results, the proposed technique has been shown to achieve the same capacity as multi-mode power loading with significantly reduced search requirements and the same amount of feedback. The advantage of the proposed scheme will be more dominant in OFDM systems with a large number of subcarriers, such as 802.11n or WiMAX.

Chapter 4

Power Loading Using Order Mapping in OFDM Systems with Limited Feedback

4.1 Background and Prior Work

Power loading plays an important role in the performance of OFDM systems in frequency selective fading. Without knowledge of the subcarrier channel gains at the transmitter, equal power loading across the subcarriers is the best strategy and shows reasonable performance in the high signal-to-noise ratio (SNR) region [86]. However, the poor performance of equal power loading at low SNR necessitates adaptive power allocation. On the other hand, waterfilling is optimal if channel state information at the transmitter (CSIT) is available [16, 82], but the amount of feedback required for full knowledge of the subcarrier channel gains is prohibitive [23, 104]. Moreover, the complexity of waterfill power loading is impractical in commercial wireless systems.

In limited feedback environments, a simple but practical approach for channel estimation is the use of comb-type channel knowledge. Instead of feeding all the channel gains back, only the channel gains of the pilot symbols are fed back to the transmitter, and then the channel gains of other subcarriers are estimated by interpolation [39, 70–74, 76]. Although the comb-type pilot structure can efficiently reduce the amount of feedback, the amount of feedback information required to determine an appropriate power level is still a burden in a limited feedback environment because emerging OFDM systems, such as [11, 12], exploit very broad spectrums.

Besides comb-type pilots, there have been several other notable techniques to reduce the amount of feedback information in OFDM systems. For example, Leke and Cioffi proposed a maximum rate loading algorithm in which the receiver feeds the on-off tone configuration back to the transmitter [75]. The required feedback amounts are reduced to N bits for OFDM systems with N subcarriers, but the threshold for on-off decisions must be adaptively determined at the receiver in time-varying channels. For OFDM power loading using the Lloyd algorithm [76, 77, 105], a codebook for power quantization is heuristically and iteratively constructed to maximize capacity. Although the Lloyd algorithm shows a decent capacity gain, it neither guarantees the globally optimized codebook nor yields any closed-form codebook. Furthermore, the heuristic and iterative codebook construction must be repeated as channels vary. Quantization errors are also sensitive to the codebook size.

Another notable technique is multi-mode power loading, which was proposed by Love and Heath [53]. In this scheme, instead of adaptively finding a threshold for the "on-off configuration", the transmitter and receiver share a codebook containing all possible on-off configurations of subcarriers. The receiver selects a codeword maximizing capacity by a brute-force search of the codebook and then feeds the index of the selected codeword back to the transmitter. Although this technique requires only N bits without an iterative procedure, the brute-force search of a codebook is impractical for OFDM systems with a large number of subcarriers, as noted in [53], because the achievable capacity for every codeword has to be calculated at the receiver during the brute-force search. Rather this approach is suitable for multiple antenna (MIMO) systems since the dimensions of MIMO systems are typically small [106, 107]. Other feedback compression techniques that originated from MIMO research [108–111] suffer from similar problems when they are applied to adaptive OFDM systems, whose dimensions are typically larger than those of MIMO systems.

To circumvent the practical shortcomings of previous adaptive OFDM techniques using limited feedback, this chapter introduces a new OFDM power loading algorithm using the order information of the subcarrier channel gains. The analysis and simulation results show that the proposed technique achieves comparable capacity and feedback reduction to previous OFDM power loading using limited feedback. In addition to this improvement, the proposed technique does not suffer from the practical drawbacks of previous power loading using limited feedback because the proposed scheme simply uses order mapping and interpolation. Compared to power loading using comb type pilots, the proposed scheme significantly reduces the required feedback amount while it achieves similar capacity to the waterfill power loading using comb type pilots.

4.2 Channel and System Models

4.2.1 Channel Model and Statistics

A collection of multiple channels for subcarriers can be modeled as a set of mutually dependent fading channels. This set of mutually dependent fading channels can be characterized by their correlation among subchannels. Let $\mathbf{h}$ be the channel vector over N subcarriers given by $[h_1\ h_2\ \cdots\ h_N]^T$. If $\mathbf{w}$ is $\mathcal{CN}(0, \mathbf{I})$ and $\mathbf{A}$ is a complex matrix, $\mathbf{h} = \mathbf{A}\mathbf{w}$ is also circular symmetric Gaussian with covariance matrix $\mathbf{\Sigma_h}$ [112]. Then the covariance matrix $\mathbf{\Sigma_h}$ is given by

$$\begin{aligned} \mathbf{\Sigma_h} &= \mathbb{E}[\mathbf{h}\mathbf{h}^*] = \mathbb{E}[\mathbf{A}\mathbf{A}^*] \\ &= \begin{bmatrix} 1 & \frac{1-j\sqrt{C}}{1+C} & \cdot & \frac{1-j(N-1)\sqrt{C}}{1+(N-1)^2C} \\ \frac{1+j\sqrt{C}}{1+C} & 1 & \cdot & \cdot \\ \vdots & \vdots & \vdots & \vdots \\ \frac{1+j(N-1)\sqrt{C}}{1+(N-1)^2C} & \cdot & \frac{1+j\sqrt{C}}{1+C} & 1 \end{bmatrix} \end{aligned} \tag{4.1}$$

where $C = 4\pi^2 \left(\frac{T_{rms}}{T_s}\right)^2$, T_{rms} is the rms delay spread, and T_s is the symbol duration [10, 113]. Then the probability density function (pdf) of $\mathbf{h}$, $p_{\mathbf{h}}(\mathbf{h})$ can be expressed by

$$p_{\mathbf{h}}(\mathbf{h}) = \frac{1}{\pi^N \det(\mathbf{\Sigma_h})} \exp\left(-\mathbf{h}^* \mathbf{\Sigma_h}^{-1} \mathbf{h}\right), \qquad \mathbf{h} \in \mathcal{C}^N. \tag{4.2}$$

Additionally, based on the covariance matrix, the correlation function between two subcarriers is given by

$$\gamma(\Delta f) = \overline{p} \frac{1 - j2\pi\Delta f \frac{T_{rms}}{T_s}}{1 + \left(2\pi\Delta f \frac{T_{rms}}{T_s}\right)^2} \tag{4.3}$$

where Δf is the subcarrier separation given by an integer and $\overline{p}$ equals the averaged power stored in one symbol.

4.2.2 System Model

Consider an OFDM system with N subcarriers. If perfect pulse shaping, sampling, synchronization, and phase recovery are assumed, the received OFDM symbol at a given symbol time can be described as $\mathbf{y} = [y_1\ y_2\ \cdots\ y_N]$. The i^{th} component of $\mathbf{y}$, y_i is given by $y_i = h_i x_i + z_i$, where h_i is a jointly complex Gaussian channel gain with N correlated elements, x_i is the transmitted signal, and z_i is independent and identically distributed (i.i.d.) Gaussian noise with mean zero and variance σ^2 for the i^{th} subcarrier. The channel gain h_i is assumed to be static during a symbol duration. Then the received OFDM symbol can be represented in a vector form by

$$\mathbf{y} = \mathbf{H}\mathbf{x} + \mathbf{n} \tag{4.4}$$

where $\mathbf{y} = [y_1\ y_2\ \cdots\ y_N]^T$, $\mathbf{H} = \mathrm{diag}(h_1, h_2, \cdots, h_N)$, where $p_{\mathbf{h}}(\mathbf{h})$ is given by (4.2), $\mathbf{x} = [x_1\ x_2\ \cdots\ x_N]^T$, and $\mathbf{n} = [n_1\ n_2\ \cdots\ n_N]^T$, where $n_i \sim \mathcal{CN}(0, N_0)$ for all i and $\mathbb{E}[n_i^* n_j] = 0$ if i$\neq$ j.

The transceiver block diagram of the adaptive OFDM system is described in Fig. 4.1. To estimate channel quality (or state) information (CQI or CSI), the transmitter periodically sends a known pilot sequence so that the channel gain or phase shift can be detected in the channel estimator of the receiver. Based on the detected channel gain, the constellation size or power

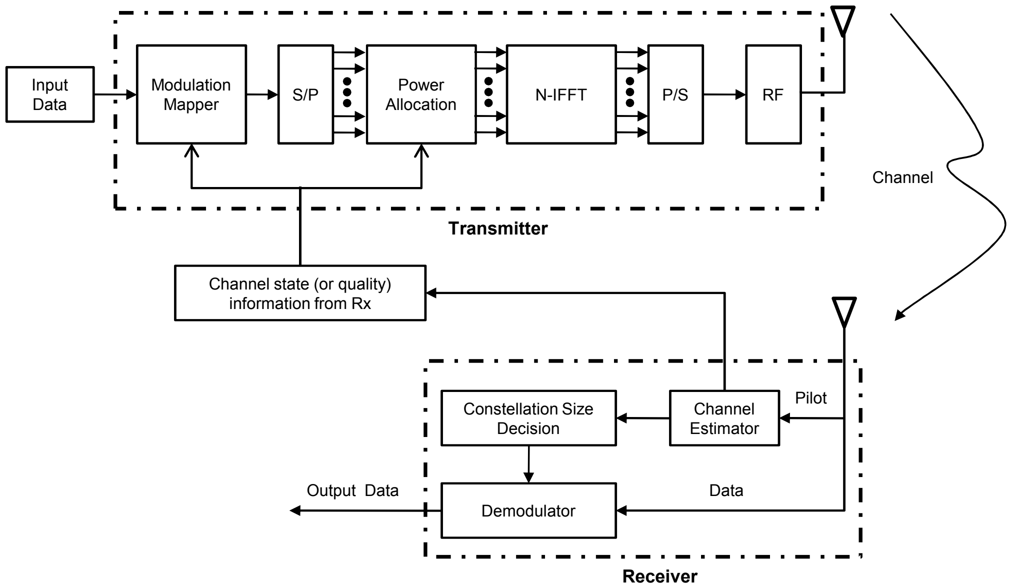

Figure 4.1: An adaptive OFDM transmitter. Modulation level or power level is adjusted by channel state (or quality) information from the receiver.

level to be transmitted is decided for the demodulator. Correspondingly, the estimator transmits collected information to the transmitter via the feedback channel. At the transmitter, rate adaptation or power adaptation is carried out based on CSIT.

4.3 Channel estimation scheme for adaptive OFDM systems

In limited feedback environments, the performance of adaptive OFDM systems is highly dependent on the accuracy of feedback. The tradeoff between limited feedback and the requirement of high spectral efficiency is a critical issue in this context. Although comb-type pilot structures achieve sufficient spectral efficiency with relatively low amount of feedback, a more efficient channel estimation scheme is required since emerging OFDM systems are exploiting larger spectrum compared to previous OFDM systems.

4.3.1 Comb-Type Channel estimation with Linear interpolation

A practical and popular way to reduce the burden of channel feedback is channel estimation using comb-type pilots [7, 70]. In a comb-type pilot structure, N_p pilots are equally spaced across subcarriers so that pilot signals are transmitted over every $L = \lfloor N/N_p \rfloor$ subcarrier. Pilot spacing, L, is normally smaller than and proportional to coherence bandwidth. Note that the comb-type pilot arrangement is sensitive to many factors, such as frequency selectivity and coherence bandwidth, so that there could be a different solution for each purpose. In this research, an equidistance pilot is applied for an optimal pilot arrangement as generally assumed in many studies [38–40].

If a perfect phase recovery is assumed, the subcarrier channel gain for the k^{th} pilot symbol is given by $\hat{h}_{kL+1}$, where $k \in \{0, \ \cdots, \ N_p - 1\}$. Then, the subcarrier channel gains between the pilot subcarriers are estimated by a linear interpolation, such as

$$|\hat{h}_{kL+l}| = \frac{|\hat{h}_{(k+1)L+1}| - |\hat{h}_{kL+1}|}{L}(l-1) + |\hat{h}_{kL+1}| \quad 1 \leq l \leq L. \tag{4.5}$$

Note that a simple linear interpolation was adopted for an example, but various other interpolation techniques can be employed. Although there could be many approaches to assigning the right-edge pilot, that is, the N_p-th pilot obtained from h_{N+1} that is not actually detected, the last subcarrier h_N, is simply repeated in this chapter as shown in [73].

Owing to the correlation between adjacent channels, the comb-type pilot structure provides a nearly perfect estimation with a smaller amount of feedback than with a block-type pilot structure [104].

4.3.2 Channel Estimation Technique Using Order Information of Pilot Channel Gains

Instead of feeding back all the subcarrier channel gains of the comb-type pilots, the channel estimation technique using order information of the pilot channel gains feeds back only the channel gain order of the comb-type pilots and the maximum and the minimum channel gains ($h_{\min}$ and $h_{\max}$) among all the comb-type pilots. The order information is transferred by an index from a predetermined codebook, $\mathcal{A}$, containing all the possible orders of subcarrier channel gains. The codebook table is shared by both the receiver and transmitter. At the transmitter, the $N_p - 2$ values between the maximum and the minimum subcarrier channel gains are obtained by interpolation. If a simple linear interpolation is considered, the j^{th} interpolated point, P_j, is represented as

$$P_j = \frac{h_{\max} - h_{\min}}{N_p - 1}(j - 1) + h_{\min} \tag{4.6}$$

where $j \in \{1, \ \cdots, \ N_p\}$. Then the interpolated values are mapped to the transmitted pilot subcarriers according to the channel gain order of the comb-type pilots. The required amount of feedback information in this technique

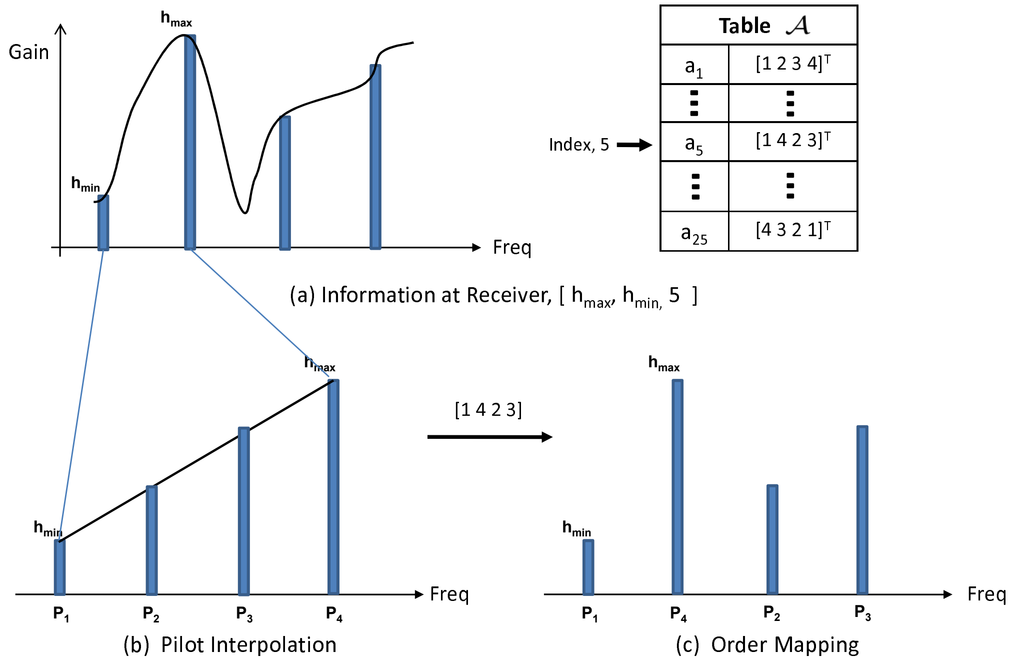

Figure 4.2: Channel estimation using gain order information. After MIN-MAX interpolation, Order mapping reconstructs pilots for channel estimation

becomes only $2B + \log_2(N_p!)$ bits because indexing all the possible orders requires $\log_2(N_p!)$ bits, and $2B$ bits are used for the feedback of $h_{\min}$ and $h_{\max}$. Once the channel gains of the transmitted pilot subcarriers are reconstructed, the channel gains of subcarriers located between the transmitted pilot subcarriers are estimated in the same way given in (4.5) for waterfill power loading.

A conceptual idea of the channel estimation technique using order information when $N_p = 4$ is illustrated in Fig. 4.2. This example assumes the channel gain order of pilot subcarriers to be [1 4 2 3], as shown in Fig. 4.2 (a), where the number denotes the pilot symbol index. In this case, the first pilot subcarrier has the smallest channel gain, and the second pilot subcarrier has the largest channel gain. Since four pilot symbols are transmitted in this comb-type pilot structure, there are 4! (= 24) possible codewords, that is, $\mathcal{A} = \{\mathbf{a_1}, \mathbf{a_2}, \cdots, \mathbf{a_{24}}\}$, for channel gain ordering. This example assumes the order [1 4 2 3], which corresponds to $\mathbf{a_5}$ in $\mathcal{A}$. Therefore, the receiver feeds $h_{\min}$, $h_{\max}$, and the index 5 back to the transmitter for channel estimation. The transmitter reconstructs the two values between $h_{\min}$ and $h_{\max}$ by interpolation, as shown in Fig. 4.2 (b). Subsequently, the interpolated values are mapped to the transmitted pilot subcarriers according to $\mathbf{a_5}$ as in Fig. 4.2 (c). As a result, the estimated channel gains by the proposed technique become similar to those by the conventional channel estimation using a comb-type pilot structure, as shown in Fig. 4.2 (a), while the amount of feedback information of the channel estimation technique using order information is considerably less.

4.4 System Analysis

To determine the effectiveness of OFDM systems with an order mapping channel estimation scheme, this section analyzes adaptive OFDM power loading techniques with an OM scheme as well as conventional adaptive OFDM power loading techniques with various feedback schemes.

4.4.1 The Amount of Feedback

The essential idea of adaptive OFDM systems is to design $\mathbf{p} = [p_1\, p_2 \cdots p_N]^T$ or to determine a proper modulation coding method based on channel gains to maximize the system capacity. In a limited feedback environment, however attaining CSIT with reasonable accuracy is a large burden in that it necessitates decreasing the required feedback. If B bits are required to feed a subcarrier channel gain back to the transmitter, the total amount of feedback for adaptive OFDM systems using conventional comb type pilots is reduced to $B_{comb} = N_p B$ bits. In comparison, block type pilots requires $B_{block} = NB$ bits feedback for the perfect CSIT in adaptive OFDM systems. As previously mentioned, channel estimation with order information requires $B_{om} = 2B + \log_2 (N_p!)$ bits feedback.

Efficiency related to comb-type pilot structure can be defined by

$$\eta = \frac{B_{comb} - B_{om}}{B_{comb}} \times 100. \tag{4.7}$$

Based on the efficiency given by (4.7) and channel correlation, the optimal size for pilot spacing, L, can be decided for the channel estimation with the OM technique.

4.4.2 Channel Estimation Accuracy

This subsection investigates the accuracy of the estimated channel gains through a comb type pilot structure and the proposed method. An effective way to evaluate the accuracy of estimation is Mean Square Error (MSE). However, the effect of an MSE value is different according to the real channel gain. That is, the significance of a MSE value is determined by the level of a real channel gain. So the normalized MSE (NMSE) [114] is considered to be defined by

$$NMSE = \frac{MSE}{E[|h|^2]} = \frac{\sum_{k=1}^{N_p} \sum_{l=1}^{L} \mathbb{E}\left[||\hat{h}_{kL+l}| - |h_{kL+l}||^2\right]}{NE[|h|^2]} \tag{4.8}$$

which measures the relative effect of MSE for a given reference value $E[|h|^2]$.

4.4.3 Capacity of various feedback schemes

The waterfilling algorithm adaptively allocates power across subcarriers according to the estimated subcarrier channel gains. The allocated power to the i^{th} subcarrier is determined by [83]:

$$\frac{p_i}{P} = \begin{cases} \frac{1}{\gamma_0} - \frac{1}{\hat{\gamma}_i} & \hat{\gamma}_i \geq \gamma_0 \\ 0 & \hat{\gamma}_i < \gamma_0 \end{cases} \tag{4.9}$$

where the cutoff value γ_0 is decided by

$$\sum_{i:\hat{\gamma}_i \geq \gamma_0} \left(\frac{1}{\gamma_0} - \frac{1}{\hat{\gamma}_i} \right) = 1. \tag{4.10}$$

Correspondingly, the achievable spectral efficiency with waterfill power allocation is given by

$$C_{avg} = \int_{\mathbf{h}} \left[\frac{1}{N} \sum_{i:\hat{\gamma}_i \geq \gamma_0} \log_2 \left(1 + \frac{|h_i|^2 P}{\sigma^2} \left(\frac{\hat{\gamma}_i - \gamma_0}{\gamma_0 \hat{\gamma}_i} \right) \right) \right] f_{\mathbf{h}}(\mathbf{h}) \; d\mathbf{h} \;\; (\text{bps/Hz}) \, . \tag{4.11}$$

Note that $\hat{h}_i$ in $\hat{\gamma}_i$ is replaced by h_i in γ_i if the channel gain estimation is perfect, which needs full CSIT.

4.5 Numerical Results

This section compares the proposed technique with various power loading techniques.

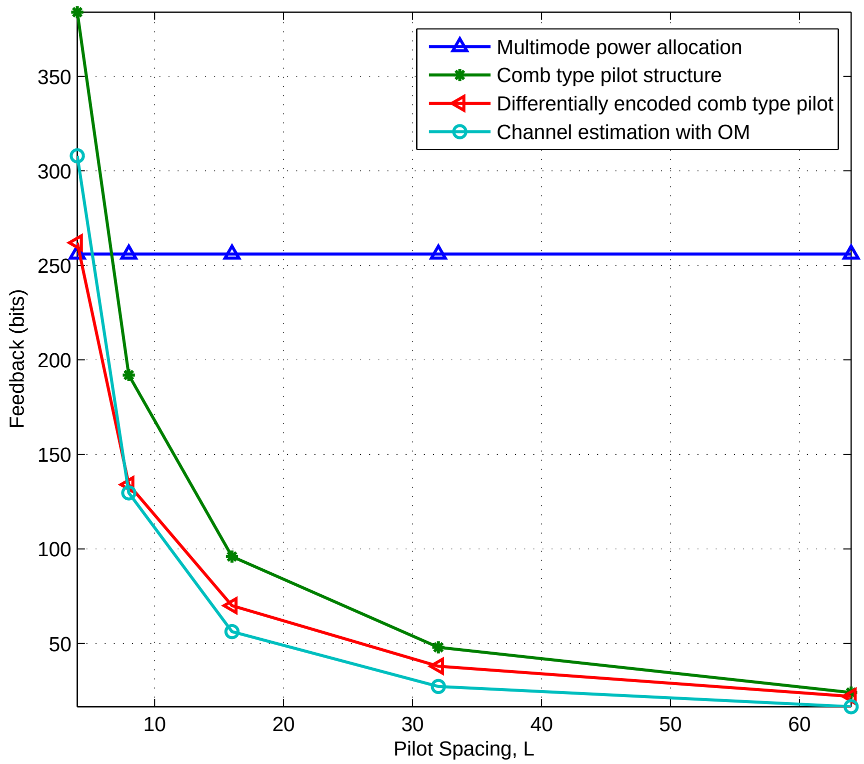

Figure 4.3: Comparison of the amount of feedback for various adaptive OFDM feedback schemes. Feedback of the OM technique shows the smallest feedback amount if pilot spacing is larger than 8.

4.5.1 Feedback Amount

Fig. 4.3 compares the required feedback amount according to pilot spacings at a given N. $B = 6$ bits is assumed for no quantization error and $N = 256$. The feedback amount of the block-type pilot structure (1536 bits) and multi-mode power loading (256 bits) is not dependent on the number of pilots, so it stays constant regardless of pilot spacing. Feedback of the block-type pilot structure is not plotted in Fig. 4.3 in order to show the difference of the various feedback schemes more clearly. As shown in [115], channel estimation with the OM technique requires less feedback than block-type pilot structure, multimode power loading systems, and comb-type pilot structure if spacing is larger than 4. For example, when the pilot spacing is 8, channel estimation with the OM technique reduces by 62 bits compared to the 192 bits of the comb-type pilot structure. Even compared with differentially encoded comb-type pilot [116, 117], channel estimation with the OM technique is more efficient in terms of the amount of feedback. The differentially encoded comb-type pilot requires $B + B_{diff}N_p$ bits, where B bits is used for the average value of pilots, B_{diff} bits is required to represent the difference of each pilot from the average value, and N_p is the number of pilots. It is assumed that $B_{diff} = 4$ bits achieves perfect quantization. Note that the differentially encoded comb type pilot is more efficient when spacing is less than 4. However, most practical systems such as those described in [11, 12, 118], mandate pilot spacing larger than 4. It should also be noted that the gap becomes larger if B or B_{diff} is increased for lower quantization error.

The efficiency of the order mapping technique over the conventional comb-type pilot structure is described in Fig. 4.4. Due to logarithmic characteristics in the feedback of channel estimation with the OM technique, the difference in amount of feedback between the comb-type pilot structure and the channel estimation with the OM technique increases almost linearly as the number of pilots increases (note that $n! \simeq n^n$ as n goes to infinity). How-

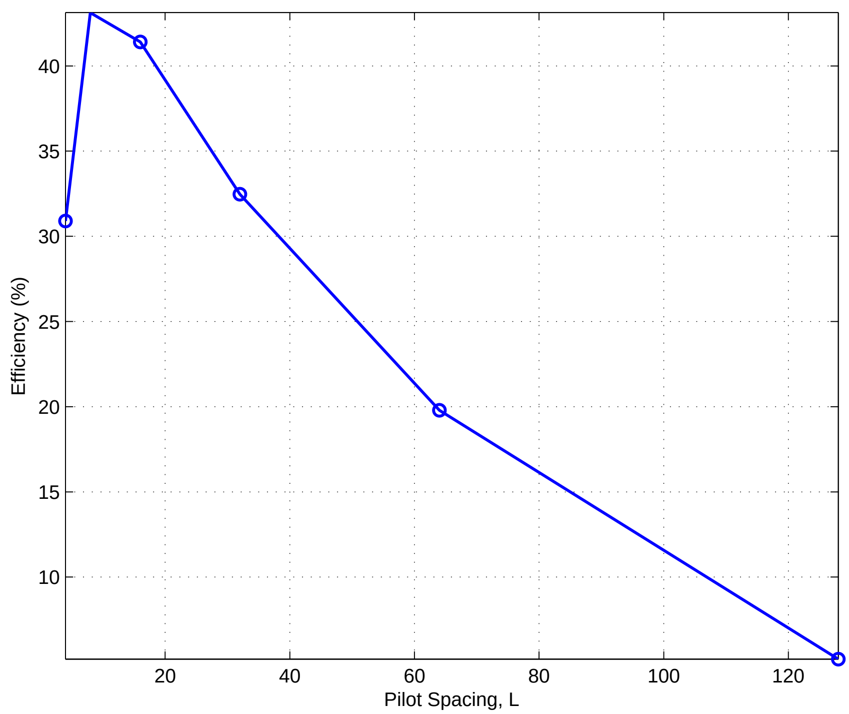

Figure 4.4: Efficiency of feedback related to comb-type pilot structure. OM technique is most efficient when L=8

ever, efficiency does not linearly increase along with the number of pilots, as shown in Fig. 4.4. Channel estimation is most efficient when pilot spacing, $L = 8$ compared to conventional comb type pilot structure. Clearly, smaller pilot spacing necessitates a larger feedback amount. In this context, tradeoff between efficiency and feedback amount needs to be carefully considered in the decision of pilot spacing, L. Considering that practical OFDM systems request pilot spacing around 8 $[11, 12]$ or 16 $[8, 118]$ on the average, channel estimations with the OM technique can achieve high efficiency for practical

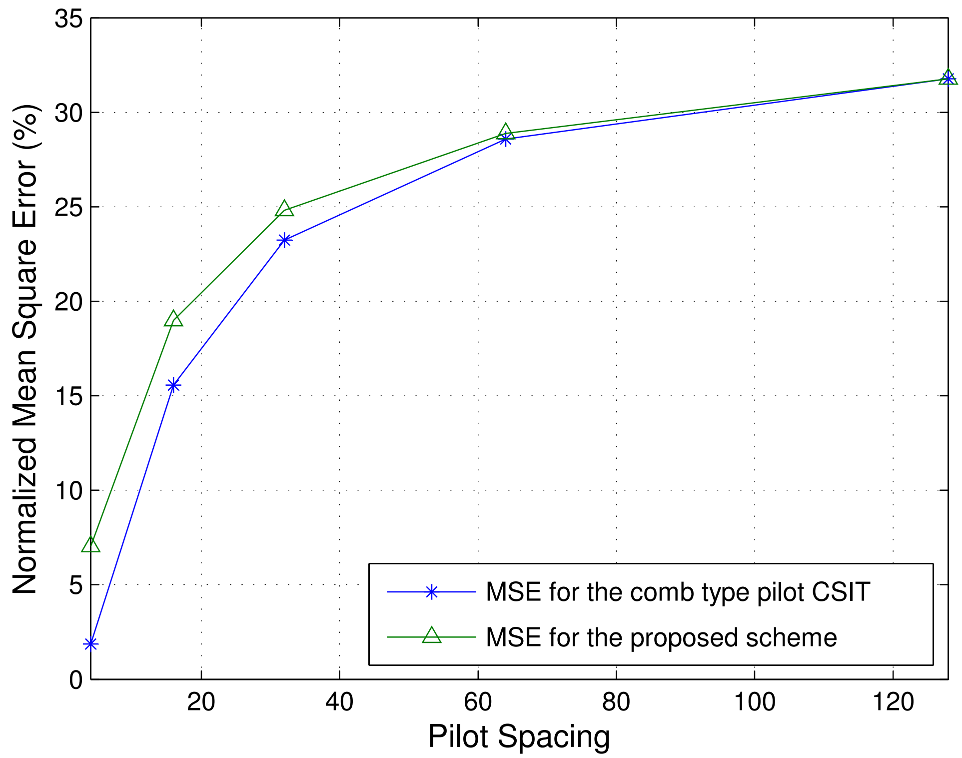

Figure 4.5: The NMSE difference between estimated channel gains with a comb type pilot structure and with the proposed scheme. The gap between a comb type pilot structure and the proposed technique is marginal

adaptive OFDM systems.

4.5.2 Comparison of Channel Estimation Accuracy

In Fig. 4.5, the normalized MSE for $E[|h|^2] = 1$ are computed and compared when $N = 128$. According to the NMSE in % shown in Fig. 4.5, the gaps of the NMSE between the comb type structure and the proposed scheme are less than 5% regardless of pilot spacing. When pilot spacing is 4, the gap of the NMSE between both schemes becomes the biggest, 5%. In this case, the MSE values for comb type pilot structure and the proposed technique are about $-17dB$ and $-12dB$, respectively. Because both $-17dB$ and $-12dB$ are sufficiently small and hence the loss in spectral efficiency due to the inaccuracy of channel estimation is expected to be marginal. Fig. 4.5 also shows that NMSE increases with pilot spacing, but the gap between a comb type pilot structure and the proposed technique diminishes as pilot spacing grows. Also it should be noted that higher channel correlation results in lower estimation error in the interpolation so that NMSE will be smaller as the channel correlation becomes high. This will results in performance improvement.

4.5.3 Comparison of Capacity

Fig. 4.6 shows achievable capacity. The achievable capacities of waterfill power loading using perfect CSIT, comb-type pilot structure, and OM technique are similar, while the required feedback of the OM technique is much less than that of the other techniques. Because the power allocation is performed with the estimated channel gain $|\hat{h_i}|$, the allocated power is not optimal if $|\hat{h_i}|$ is incorrect. As the channel estimation error becomes larger, the capacity loss from the achievable capacity by the optimal power allocation becomes significant. The MSE values for comb type pilot structure and OM technique are sufficiently small as explained in the previous subsection. Therefore, the capacity loss from the comb-type pilot due to the inaccuracy of channel estimation becomes marginal, as shown in Fig. 4.6. Because performance gap from equal power loading increases as SNR decreases, the effectiveness of OM

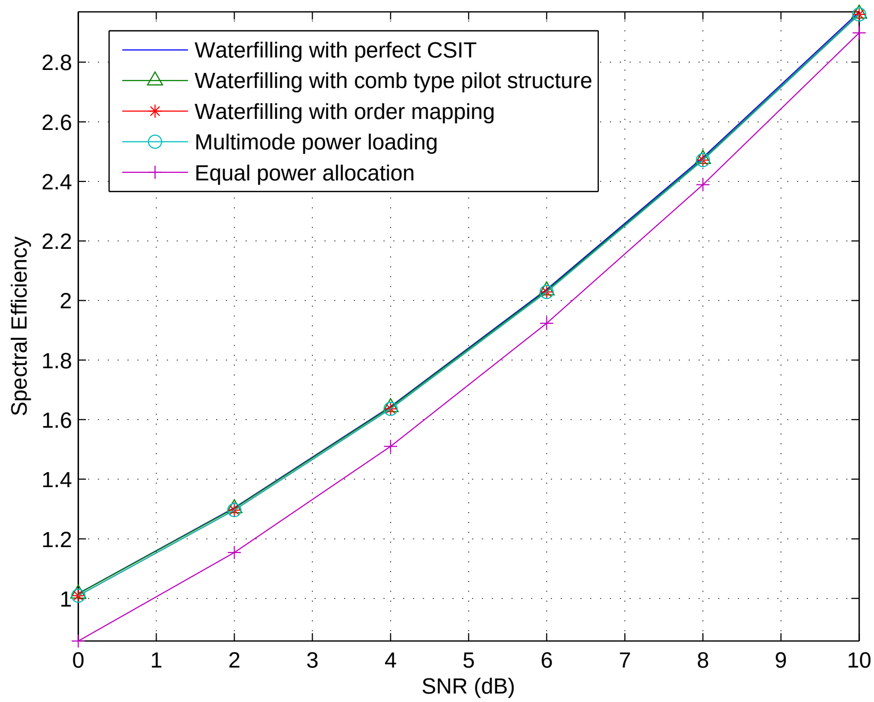

Figure 4.6: Spectral efficiency of various power allocation techniques. The feedback technique using OM technique achieves almost the same spectral efficiency compared to previous feedback schemes.

technique is more viable when SNR range is low. Also, it should be noted that the OM scheme is less sensitive to quantization errors than other techniques since it utilizes channel gain order information instead of the exact channel gain values.

The advantage of the proposed scheme can be also shown by capacity comparison with the same feedback amount. For example, the total required feedback is 31 and 30 bits for the proposed scheme and the comb type pilot scheme when $L = 4$ and 6-bit quantization are applied. T_{rms}/Ts is set to be 0.11. When SNR is 5dB and the bandwidth is 20MHz, the throughput gain is about 278Kbps($=$ 0.0139bps/Hz $\times$ 20MHz) over the comb type scheme, while the throughput loss from the optimal capacity is about 492Kbps($=$ 0.0246bps/Hz$\times$20MHz). Eventually, the proposed scheme achieves about 35% enhancement in throughput loss because the comb type scheme has 770Kbps throughput loss from the optimal capacity. Alternatively, the gain of the proposed scheme can be quantified in terms of the total amount of required feedback. When the pilot spacing is 8 for a 64 subcarrier system and the quantization level is 4 bits, spectral efficiencies of both the proposed scheme and the comb-type scheme become the same in a correlated channel with $T_{rms}/T_s = 0.11$. In this case, the total required feedback bits of the proposed scheme and the comb-type scheme are 27 and 36 bits, respectively. The difference of the required feedback bits increases with quantization level and the total number of subcarriers. Compared to multimode power loading, the OM technique achieves almost the same spectral efficiency and feedback reduction. It should be noted, however, that multimode power loading needs a brute-force search to find the best codeword among 2^N codewords. As discussed in [53], multimode power loading becomes infeasible as N increases due to the computational complexity at the receiver.

4.6 Conclusion

This chapter has proposed a novel power loading technique of OFDM systems using subcarrier channel gain order information. The analysis and simulation results show that the proposed technique achieves comparable capacity to optimal waterfill power loading with perfect CSIT, while requiring significantly less feedback information. It has been also shown that the proposed technique is more practical than other OFDM power loading techniques using limited feedback while achieving almost the same capacity and better feedback reduction. The advantage of the proposed technique becomes most apparent in the low SNR region or in OFDM systems with a large number of subcarriers, where practical multiuser or multicellular OFDM systems are operated.

Chapter 5

Adaptive Coding and Modulation Technique Using Order Mapping for Feedback Reduction

5.1 Introduction

Among the technologies for enhancing the performance of OFDM systems, channel adapted techniques, such as power loading and adaptive modulation and coding (AMC) [17, 57, 62–67], have been popular and effective in frequency selective fading channels.

The basic concept of these adaptive OFDM systems is to achieve optimal throughput by adaptive variation of the transmitted power level, the constellation size, the coding technique, or any combination of these based on channel variations. For this reason, the performance of adaptive OFDM systems is highly dependent on the accuracy of channel estimation at the receiver. In this context, full CSIT is most desirable, but a limited spectrum usage of feedback restricts the use of full CSIT [23, 104].

To circumvent the practical shortcomings of previous adaptive OFDM techniques using limited feedback, the previous chapter introduced an OFDM power loading algorithm using order information of the subcarrier channel gains. The proposed channel estimation scheme for adaptive OFDM systems achieves capacity and feedback reduction comparable to those of previous OFDM power loading techniques using limited feedback. In addition to this improvement, the technique proposed in Chapter 4 does not suffer from the practical drawbacks of previous power loading using limited feedback, such as sensitivity to quantization error, large feedback amount, and large search amount because it simply utilizes order mapping and interpolation.

In this chapter, we extend the analysis of OFDM systems using OM technique to adaptive OFDM systems, including AMC per subcarrier and cluster. Multidimensional coded variable-rate M-QAM given in [78] is considered for AMC. Unlike power loading, an analysis of the AMC technique gives more practical insight because the throughput and bit error rate (BER) of AMC are more correlated to estimation error. The analytical approach in this chapter will show the effectiveness of the OM technique in a practical sense. The analysis and simulation show that adaptive OFDM systems using the OM technique show a comparable performance to conventional adaptive OFDM systems in terms of bit error rate (BER) and throughput while the required feedback amount is still significantly reduced by approximately 30% compared to a conventional comb type pilot structure, as shown in the analysis in Chapter 4. Additionally, the advantages described in Chapter 4 over previous power loading techniques using limited feedback remains when the OM technique is applied to OFDM systems with AMC.

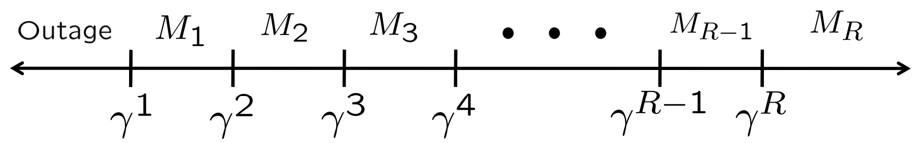

Figure 5.1: BER comparisons between comb type pilot structure and channel estimation using OM technique. BER of both schemes are below target BER and marginal.

5.2 System Model

In this chapter, the jointly complex Gaussian channel [112] and system model described in section 4.2 are assumed. While the previous chapter analyzed the OM technique under adaptive power loading, this chapter will analyze adaptive OFDM systems using the OM technique under more practical discrete-rate M-QAM scheme in a jointly complex Gaussian channel model.

In the ACM OFDM system described in Fig. 4.1, the transmitter decides on a rate of $\log_2 M_n$ bits per subcarrier based on a SNR range. The SNR range is split into R+1 regions, such that $M_1 < M_2 < \cdots < M_R$ as shown in Fig. 5.1. When the estimated SNR falls into the lowest SNR interval, no data is transmitted, which is referred to as outage. R+1 regions are typically decided as the lowest SNR region to operate at a lowest BER, called the target BER, BER_0, with limited power P. We define γ^n as the lowest SNR at BER_0 for a constellation size M_n.

5.3 System Analysis

5.3.1 BER Analysis

The Shannon capacity defines the maximal achievable rate of data transmission for an arbitrarily small BER. For this reason, the Shannon capacity can be an upper bound for practical adaptive communication schemes. However, a practical limit such as channel estimation error or noncontinuous coded modulation decreases spectral efficiency or BER performance. To verify the effectiveness of adaptive OFDM systems with the OM technique in practical environments, constant power with ACM developed in [66, 78] is considered.

The average BER for ACM OFDM systems can be defined as the ratio between the average bits of error and the average bits per symbol transmitted for one OFDM symbol and expressed by

$$\overline{\mathrm{BER}} = \frac{\sum_{n=1}^{R} n\overline{\mathrm{BER}}_n}{\sum_{n=1}^{R} n p_n} \tag{5.1}$$

where $\log_2 M_n = n$, p_n is the probability that code n will be used, and $\overline{\mathrm{BER}}_n$ is BER for code n averaged over all SNR and subcarriers [65].

Let SNR of the i^{th} subcarrier be $\hat{\gamma}_i = |\hat{h}_i|^2 P/\sigma^2$, then the probability p_n is

$$p_n = \frac{1}{N}\sum_{i=1}^{N}\int_{\gamma^n}^{\gamma^{n+1}} p_{\hat{\gamma}_i}(\hat{\gamma}_i)\, d\hat{\gamma}_i = \frac{1}{N}\sum_{i=1}^{N}\int_{\hat{h}_i\hat{h}_i^* \in [\frac{\gamma^n\sigma^2}{P}, \frac{\gamma^{n+1}\sigma^2}{P})} p_{\hat{h}_i}(\hat{h}_i)\, d\hat{h}_i \tag{5.2}$$

which is simply the probability that the estimated SNR for each subcarrier lies in $[\gamma^n, \gamma^{n+1})$.

If an i.i.d complex Gaussian channel, and a perfect channel estimation are assumed, $\hat{\mathbf{h}} = \mathbf{h}$, then p_n is simplified by

$$p_n = \Gamma\left(1, \frac{\gamma_n}{\bar{\gamma}}\right) - \Gamma\left(1, \frac{\gamma_{n+1}}{\bar{\gamma}}\right) \tag{5.3}$$

where $\Gamma(.,.)$ is the complementary incomplete gamma function [119].

The average BER for code n is the BER averaged over all SNR and subcarriers when the estimated SNR is $\hat{\gamma} = [\hat{\gamma}_1, \hat{\gamma}_2, \cdots, \hat{\gamma}_N]$ and is given by

$$\overline{\mathrm{BER}}_n = \frac{1}{N}\sum_{i=1}^{N}\int_{\gamma_n}^{\gamma_{n+1}}\int_0^{\infty}\mathrm{BER}(M_n, \gamma_i|\hat{\gamma}_i)p_{\gamma_i,\hat{\gamma}_i}(\gamma_i, \hat{\gamma}_i)\; d\gamma_i\; d\hat{\gamma}_i \tag{5.4}$$

where $\mathrm{BER}(M_n, \gamma_i|\hat{\gamma}_i)$ is BER for the n^{th} SNR region and the i^{th} subcarrier, and $p_{\gamma_i,\hat{\gamma}_i}(\gamma_i, \hat{\gamma}_i)$ is the joint distribution of the actual and the estimated SNR. $\mathrm{BER}(M_n, \gamma_i|\hat{\gamma}_i)$ for multidimensional trellis codes on AWGN channels is demonstrated in [66, 78] as

$$\mathrm{BER}(M_n, \gamma|\hat{\gamma}) = \begin{cases} a_n \exp\left(\frac{-b_n\gamma}{M_n}\right) & \text{when} \gamma \geq \gamma_T \\ 0.5 & \text{when} \gamma < \gamma_T \end{cases}$$

where a_n and b_n are parameters found by least-square curve fitting, and M_n is the constellation size.

Note that a_n, b_n, and M_n are chosen to be matched with the estimated SNR $\hat{\gamma}$, while the exact SNR value γ is exploited for $\mathrm{BER}(M_n, \gamma|\hat{\gamma}_i)$ calculation. Since BER cannot become larger than 0.5, the threshold SNR is defined as $\gamma_T = \frac{\ln(2a_n)M_n}{b_n}$, the smallest SNR guaranteeing that BER does not exceed 0.5.

Although an asymptotic analysis that assumes an i.i.d complex Gaussian channel and perfect channel estimation shows the general behavior of pilot-aided adaptive OFDM systems, it is difficult to anticipate the performance difference between conventional comb-type structure and pilot structure using the OM technique with the asymptotic approach. While the asymptotic analysis regarding comb-type pilot-aided OFDM systems is able to effectively evaluate the performance difference between perfect channel estimation and pilot-aided channel estimation, it is not capable of analyzing performance differences between pilot-aided channel estimation schemes. In this context, Monte Carlo integration has been used for (5.2) and (5.4) rather uses asymptotic analysis such as (5.3) or a bivariate gamma distribution for $p_{\gamma,\hat{\gamma}_i}(\gamma, \hat{\gamma}_i)$ in [78, 120].

5.3.2 Comparison of Average Spectral Efficiency (ASE)

The actual achievable rate using $2G$-dimensional trellis codes is obtained by [78]:

$$R_n = \left(\log_2 M_n - \frac{1}{G}\right) \tag{5.5}$$

where G is some positive integer according to the dimension of the trellis code. Then the average spectral efficiency (ASE) is defined by the average number of bits per second per Hz. Typically, this value can be obtained by

$$\begin{aligned} R_{avg} &= \sum_{n=1}^{R} R_n \cdot p_n = \sum_{n=1}^{R} \left(\log_2 M_n - \frac{1}{G}\right) \cdot p_n \\ &= \sum_{n=1}^{R} \left[\left(\log_2 M_n - \frac{1}{G}\right) \cdot \frac{1}{N} \sum_{i=1}^{N} \int_{\gamma^n}^{\gamma^{n+1}} p_{\hat{\gamma}_i}(\hat{\gamma}_i)\ d\hat{\gamma}_i \right]. \end{aligned} \tag{5.6}$$

On the other hand, constellation size, M_n, is determined under the constraint of the target BER, BER_0. For this reason, ASE must be a meaningful performance measure only when BER becomes lower than BER_0. The received data is no longer reliable as long as BER is above BER_0. To satisfy this strict constraint, (5.2) can be modified by

$$p_n = \frac{1}{N}\sum_{i=1}^{N}\int_{\gamma^n}^{\gamma^{n+1}} p_{\hat{\gamma}_i}(\hat{\gamma}_i)\cdot \mathbf{1}[\mathrm{BER}(M_n,\hat{\gamma}_i) \le \mathrm{BER}_0]\; d\hat{\gamma}_i \tag{5.7}$$

where $\mathbf{1}[x]$ is the indicator function with $\mathbf{1}[x] = 1$ if the condition x is satisfied and $\mathrm{BER}(M_n, \hat{\gamma}_i)$ is the BER for code n when the estimated SNR for i^{th} subcarrier is $\hat{\gamma}_i$. ASE is eventually defined as

$$\begin{aligned} R_{avg} &= \sum_{n=1}^{R} R_n \cdot p_n = \sum_{n=1}^{R}\left[\left(\log_2 M_n - \frac{1}{G}\right)\right. \\ &\quad \left. \cdot \frac{1}{N}\sum_{i=1}^{N}\int_{\gamma^n}^{\gamma^{n+1}} p_{\hat{\gamma}_i}(\hat{\gamma}_i)\cdot \mathbf{1}[\mathrm{BER}(M_n,\hat{\gamma}_i) \le \mathrm{BER}_0]\; d\hat{\gamma}_i\right]. \end{aligned} \tag{5.8}$$

5.3.3 Clustered OFDM systems

In discrete ACM OFDM systems, ACM allocation per subcarrier can be an optimal for the capacity but inefficient when the channel is highly correlated between adjacent channels. In this context, a practical approach in correlated channel is actually the use of clustered (or blocked) OFDM systems that exploit the channel blocks as a smallest resource allocation unit rather than one subcarrier [79, 88, 121, 122]. In clustered OFDM systems, one representative value is normally fed back to the transmitter for one subchannel cluster. This representative value can be the smallest, highest, or averaged SNR value among the SNR of pilots in one cluster.

The only difference in analysis between OFDM systems using AMC per subcarrier and per cluster is that all the estimated channel gains in one cluster are the same as the representative value fed back for that cluster. For example, if the average SNR of pilots in one cluster is used for a representative value, a representative value of the k^{th} cluster, $\gamma_{rep,k}$, is defined as

$$\gamma_{rep,k} = \frac{L}{T} \sum_{i=1}^{N_{rep}} \hat{\gamma}_{T(k-1)+L(i-1)+1} \quad 1 \leq k \leq N_c \tag{5.9}$$

where T is size of cluster, $\lfloor N_{rep} = T/L \rfloor$ is the number of pilots in a cluster, and $N_c = N/T$ is the number of clusters. Then, SNR for each subcarrier can be obtained by

$$\hat{\gamma}_i = \gamma_{rep,\lfloor i/T+1 \rfloor}. \tag{5.10}$$

Conventional clustered OFDM systems feed representative SNR values back to the transmitter directly. Therefore, the amount of required feedback is BN_c bits. On the other hand, if order information among $[\gamma_{rep,1}, \cdots, \gamma_{rep,N_c}]$ is used, the required amount of feedback is $2B + \log_2 N_c!$ bits, where 2B bits are used for the maximum and minimum value, γ_{max} and γ_{min}, respectively, among $[\gamma_{rep,1}, \cdots, \gamma_{rep,N/T}]$. For example, Fig. 4.2 can be exactly applied for a clustered OFDM systems if pilots are replace with representative values for clusters.

Once each $\hat{h}_i$ or $\hat{\gamma}_i$ is determined, BER and R_{avg} for clustered OFDM systems can be obtained from (5.1) and (5.8), respectively.

Table 5.1: Parameters, a_n and b_n, and calculated threshold, γ_n, for target $BER_0 = 10^{-4}$.

n	M_n	a_n	b_n	γ_n[dB]
1	4	188.7471	9.8118	7.7
2	8	288.8051	6.8792	12.4
3	16	161.6898	7.8862	14.6
4	32	142.6920	7.8264	17.6
5	64	126.2118	7.4931	20.8
6	128	121.5189	7.7013	23.7
7	256	79.8360	7.1450	26.9
8	512	34.6128	6.9190	29.7

5.4 Numerical Results

In this section, the performance of adaptive OFDM systems using the OM technique is compared to adaptive OFDM systems with various feedback schemes. To present the advantages of the OM technique for adaptive OFDM systems, adaptive multidimensional coded modulation has been considered for a numerical example. Parameters for the BER expression and capacity of discrete OFDM systems, such as a_n, b_n, γ_T, and M_n, are summarized in Table 5.1.

5.4.1 BER Performance

This subsection compares BER performance of adaptive OFDM systems with conventional comb-type pilot structure to those using the OM technique. $N = 64$ and $L = 16$ is assumed corresponding to [7, 9]. ACM parame-

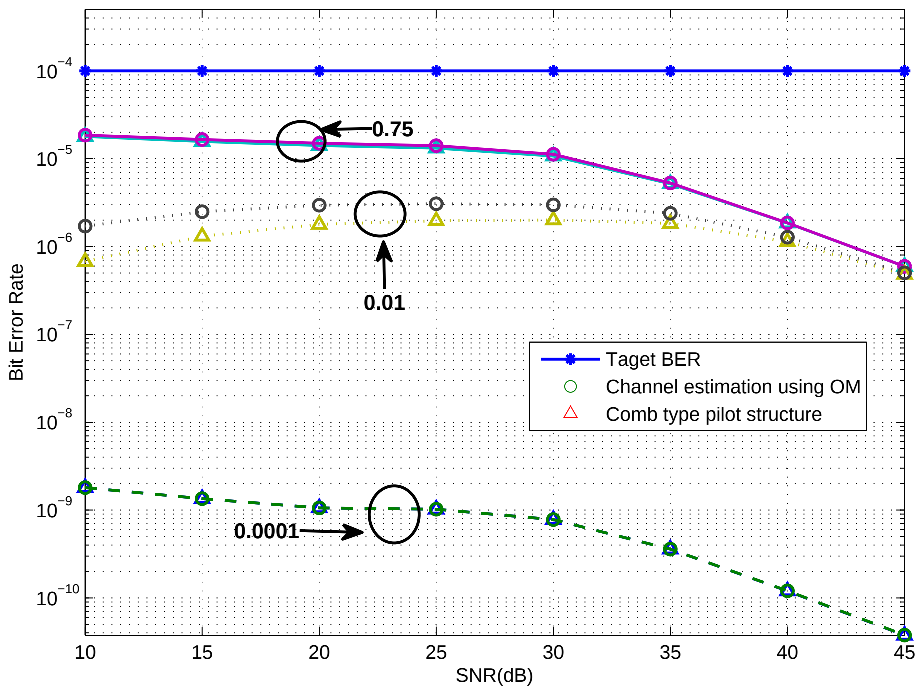

Figure 5.2: BER comparisons between comb type pilot structure and channel estimation using OM technique. BER of both schemes are below target BER and marginal.

ters have been chosen for target $\text{BER}_0 = 10^{-4}$. In Fig. 5.2, BER performances based on different correlation parameters, T_{rms}/T_s, have been illustrated.

In Fig. 5.2, it is observed that the average BER for both schemes are enhanced as the subcarrier channels become more correlated. Note that subcarrier channels become more correlated as T_{rms} becomes smaller relative to T_s. When $T_{rms}/T_s = 0.75$, the BERs for both schemes are under target $\text{BER}_0 = 10^{-4}$ and almost the same. This similarity in BER performance of both schemes results from the characteristics of uncorrelated subcarrier channels. Because the accuracy of channel estimation using the comb-type pilot structure and the OM scheme is dependent on channel correlation, there is no difference in BER performance when both systems do not estimate subcarrier channel gain accurately because of low subcarrier channel correlation. When $T_{rms}/T_s = 0.01$, subcarrier channels have become more correlated so that the BER performance of both schemes is enhanced compared to BER at $T_{rms}/T_s = 0.75$. On the other hand, the BER of adaptive OFDM systems using a comb-type pilot structure shows slightly better but marginal BER performance compared to that of adaptive OFDM systems using the OM technique. This performance gap decreases again as subcarrier channels become more correlated because the channel estimation using order mapping becomes as accurate as channel estimation using comb-type pilot structure. Additionally, since no quantization error for the comb-type pilot structure is assumed, adaptive OFDM systems with comb-type pilot structure show slightly better performance gain compared to adaptive OFDM systems using the OM technique. If quantization error is considered, this insignificant performance gap can be ignored. A performance comparison when quantization is considered is investigated in 4.5.4. Please see 4.5.4 for more details. If $T_{rms}/T_s = 0.0001$, both techniques estimate subcarrier channel gains with high accuracy, so adaptive OFDM systems using both schemes very good BER performance, and there is no performance gap between the two schemes. Considering that T_{rms}/T_s lies between 0.01 and 0.0001 in practical situations, adaptive OFDM systems using

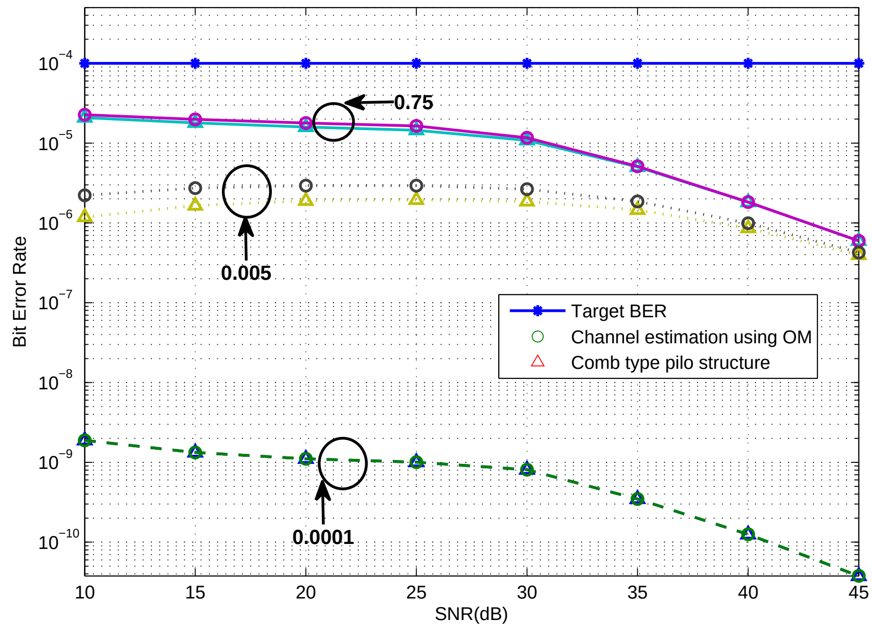

Figure 5.3: BER comparisons between comb type pilot structure and channel estimation using OM technique for clustered OFDM systems. Clustered adaptive OFDM systems show similar tendency in performance to adaptive OFDM systems with ACM per subcarrier.

channel gain order information are able to achieve marginal BER performance while using smaller amount of feedback, as shown in Fig. 4.4.

BER performance of clustered OFDM systems using ACM is plotted in Fig. 5.3, where simulation parameters are $N = 128$, $L = 16$, $T = 16$ and $N_{rep} = 1$. As predicted, the clustered OFDM systems using ACM show a tendency similar to that of OFDM systems using ACM per subcarrier in BER performance. Both adaptive OFDM systems with comb-type pilot structure and with OM techniques achieve better BER if the subcarrier channels are more correlated. Moreover, it exploits a representative value for all subcarrier channels in one cluster. Therefore, the performance gap between clustered OFDM systems using comb-type structure and OM techniques must be less compared to that of the ACM per subcarrier, as explained in the previous paragraph. Additionally, the BER at $T_{rms}/T_s = 0.005$ in Fig. 5.3 is actually similar to the BER at $T_{rms}/T_s = 0.01$ in Fig. 5.2. Since clustered OFDM systems exploit a representative value for a cluster, they require equal or less feedback, and there is no complex procedure for subcarrier channel reconstruction. On the other hand, performance degradation compared to that of the ACM per subcarrier would be unavoidable. In this example, BER at $T_{rms}/T_s = 0.005$ is worse than BER at $T_{rms}/T_s = 0.005$ in Fig. 5.2, while it satisfies the requirement of the target BER_0. Note that the BER performance of ACM per subcarrier and ACM per cluster is same when subcarrier channels are highly correlated ($T_{rms}/T_s = 0.0001$) or highly uncorrelated ($T_{rms}/T_s = 0.75$).

Eventually, adaptive OFDM systems using order information of subcarrier channel gains achieves marginal BER performance compared to that of the comb-type pilot structure in both OFDM systems using ACM per subcarrier and cluster. Moreover, the OM technique is more efficient when it applies to clustered OFDM systems. The OM technique of clustered OFDM systems achieves same feedback reduction while it avoids additional complexity required to reconstruct subcarriers in clustered OFDM systems.

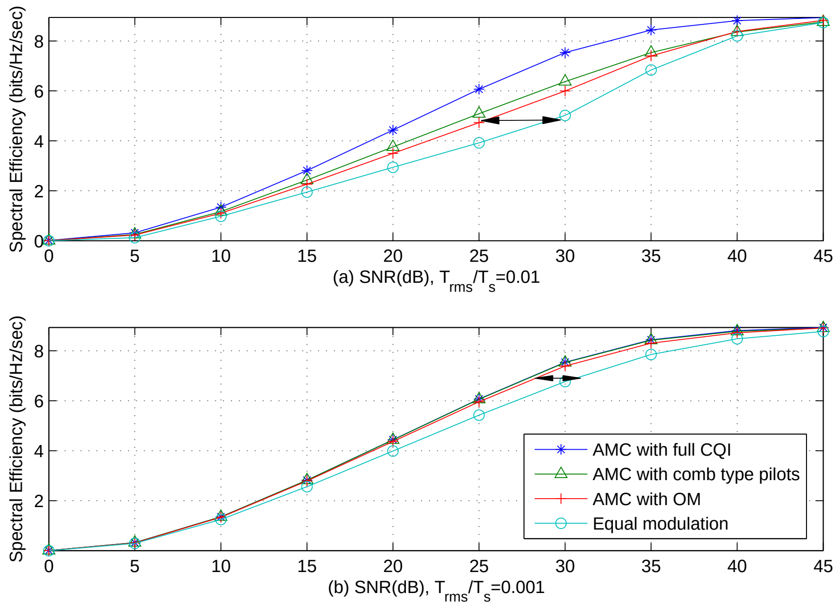

Figure 5.4: Spectral Efficiency of adaptive OFDM systems with various feedback schemes

5.4.2 ASE Performance

BER analysis is an important performance measure in reliable communication. From a practical point of view, the BER can be largely divided into two regions: an acceptable region (smaller than BER_0) and an unacceptable region (larger than BER_0) [78]. In this context, once the system is operating in the acceptable BER region, the key performance measure is the ASE. Using the derivation in (5.8), the ASEs for different subcarrier channel correlations are presented in Fig. 5.4. From this figure, it can be noted that the difference of ASE from adaptive OFDM systems with full CSIT to adaptive OFDM systems with the comb-type structure and OM scheme, and OFDM systems with equal modulation decreases as subcarrier channels are more correlated. When $T_{rms}/T_s = 0.01$, ASE difference between adaptive OFDM systems using comb type pilots and OM technique is marginal. While the largest gain of the OM technique is about 5dB compared to equal modulation, a similar gap is observed from full CSIT. On the other hand, when $T_{rms}/T_s = 0.001$, the ASE differences among the full CSIT, the comb-type pilot structure, and the OM technique become negligible due to the high correlation among subcarrier channels. The ASE of adaptive OFDM systems using the OM technique does not only reach optimal ASE, but it still outperforms equal modulation schemes, as shown in Fig. 5.4 (b). In Fig. 5.4, the ACM using OM technique requires 17 bits, which is about 30% less feedback than the ACM using comb-type pilot structure. If the total number of subcarriers N is increased, the effectiveness of channel estimation using OM technique will be more significant.

The ASE of adaptive clustered OFDM systems is described in Fig. 5.5. As predicted in the BER performance of adaptive clustered OFDM systems, the ASEs of adaptive clustered OFDM systems with the comb-type pilot structure and OM technique are both degraded compared to the ASE of the adaptive OFDM system using ACM per subcarrier. However, the general behaviors of both schemes are exactly the same as in the previous case. It is observed that the ASE difference between adaptive clustered OFDM systems using comb-type pilot structure and OM scheme is marginal. Similar to the trend shown in Fig. 5.4, the performance gap between adaptive clustered OFDM systems with full CSIT and OM technique becomes insignificant as

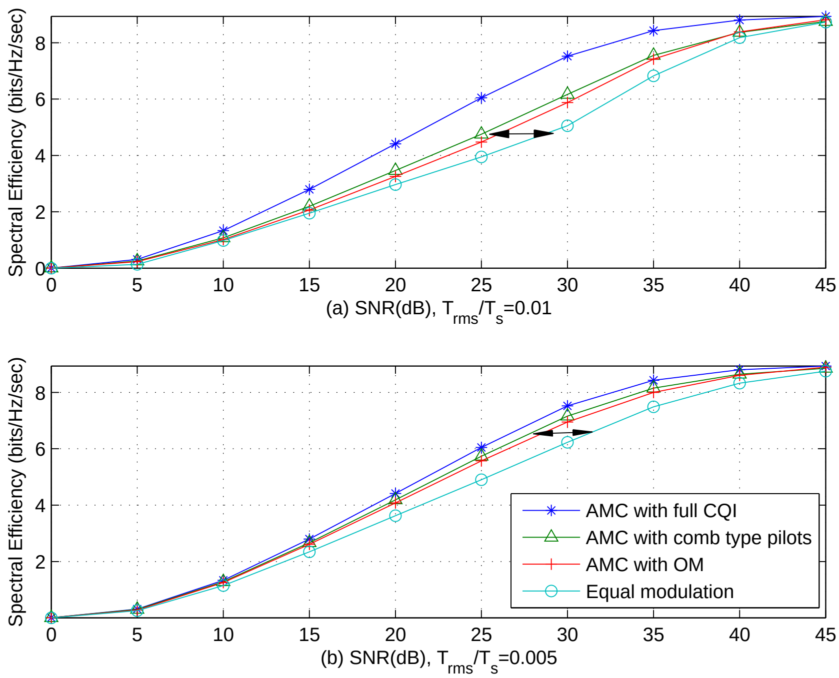

Figure 5.5: Spectral Efficiency of adaptive clustered OFDM systems with various feedback schemes

the subcarrier channels becomes highly correlated, as shown in Fig. 5.5 (a) and (b). Note that the ASE of adaptive clustered OFDM systems with the OM technique has been achieved with the same about 30% drop in feedback as in the case of adaptive OFDM systems using ACM per subcarrier.

5.4.2.1 ASE Comparison with Practical Parameters

While equally spaced pilot structure is known to be optimal for the maximal ASE [38–40], the most recent and best known approach for the comb type pilot can be found in 802.16e or 3GPP LTE. Note that reference signals,

Table 5.2: Simulation parameters

Parameter	Value
Speed, v	15 km/h
Carrier Frequency	2 GHz
Doppler Spread, f_m	$v/\lambda = 28$ Hz
Coherence Time, T_c	$\sqrt{\frac{9}{16 \cdot \pi \cdot f_m^2}} = 15.7$ ms
Symbol Duration, T_s	66.663 μs
Size of PRB	12 subcarriers

instead of pilot signals, are used for the channel estimation in 3GPP LTE. Fig. 5.6 shows channel estimation techniques in both schemes. The key idea of both approaches is that pilots (or reference signals) are staggered in both time and frequency by allocating pilots to two different positions. For example, reference signals are transmitted every sixth subcarrier for the channel estimation in 3GPP LTE, as shown in Fig. 5.6. In one slot, consisting of seven OFDM symbols, the first and fifth symbols are used for the channel estimation. In the fifth OFDM symbol in the slot, reference signals are allocated in the middle of two reference signals for the first OFDM symbols in the slot. By changing the position of the reference signals, it is possible to avoid deep-fading within two reference signals. The same philosophy is exploited in the DL PUSC cluster structure of 802.16.

To verify the effectiveness of the proposed scheme in the most recent comb type channel estimations, the performance of the proposed OM technique is analyzed in the same environment of 3GPP LTE. Based on the requirement

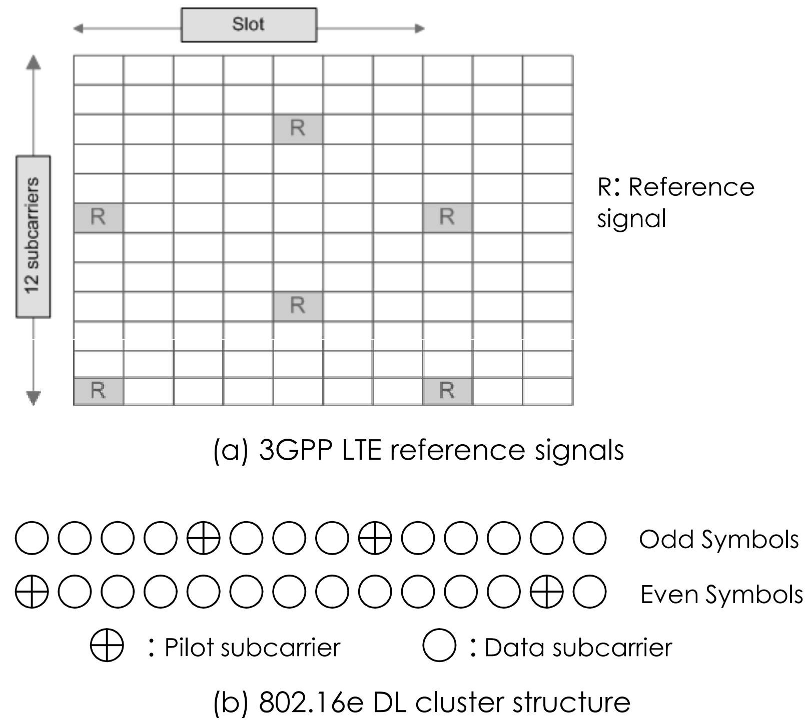

Figure 5.6: Pilots or reference signals in emerging wideband wireless communication systems

for 3GPP LTE, the systems supports high mobile speed between 15 $\sim$ 120 km/h with high performance. In this subsection, 15 km/h is assumed. The maximum delay spread for the fixed broad wireless communication is specified by the Stanford University Interim (SUI) channel model. The worst rms delay spread in SUI-6 is $5.24\mu s$. The International Telecommunications Union (ITU-R) Vehicular Channel Model B [123] shows the delay spread values of up to $20\mu s$ for mobile environments. Considering a mobile environment, $0.001 \leq T_{rms}/T_s \leq 0.1$ can be used for the channel correlation. The simulation parameters are summarized in Table. 5.2. Note that physical resource block

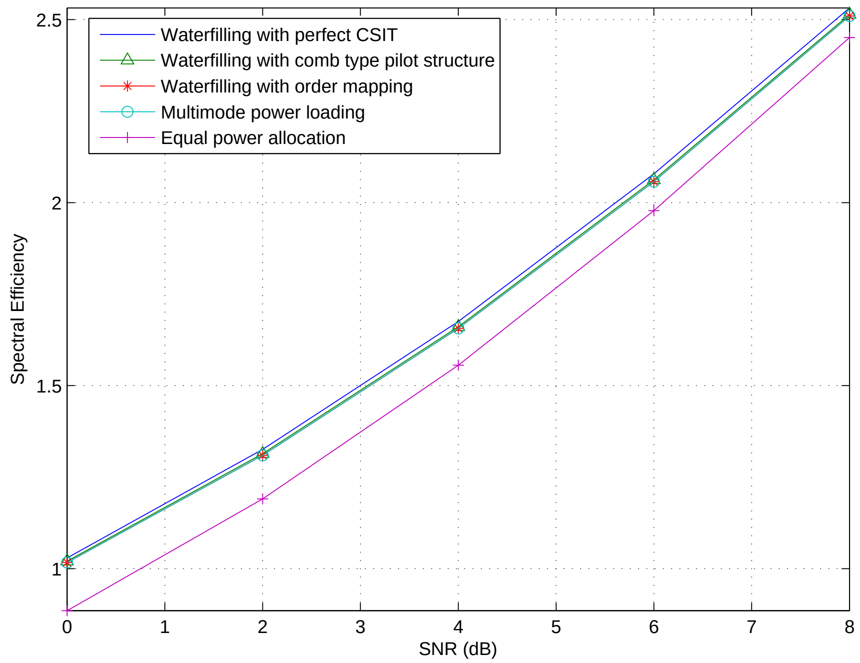

Figure 5.7: ASE comparison of various feedback schemes with parameters of 3GPP LTE

(PRB) in 3GPP LTE is the same as the cluster.

In Fig. 5.7, the achievable capacities of waterfill power loading using pilot structure in 3GPP LTE, as shown Fig. 5.6, are described. Eight reference signals are used for the channel estimation, and the proposed scheme eventually reduces the amount of feedback by approximately 40%. Although different pilot positions are considered between the first and fifth OFDM symbols in a slot, the achievable capacities of waterfill power loading using perfect CSIT, comb-type pilot structure, or the OM technique are similar, while the required feedback of the OM technique is still much less than that of the other

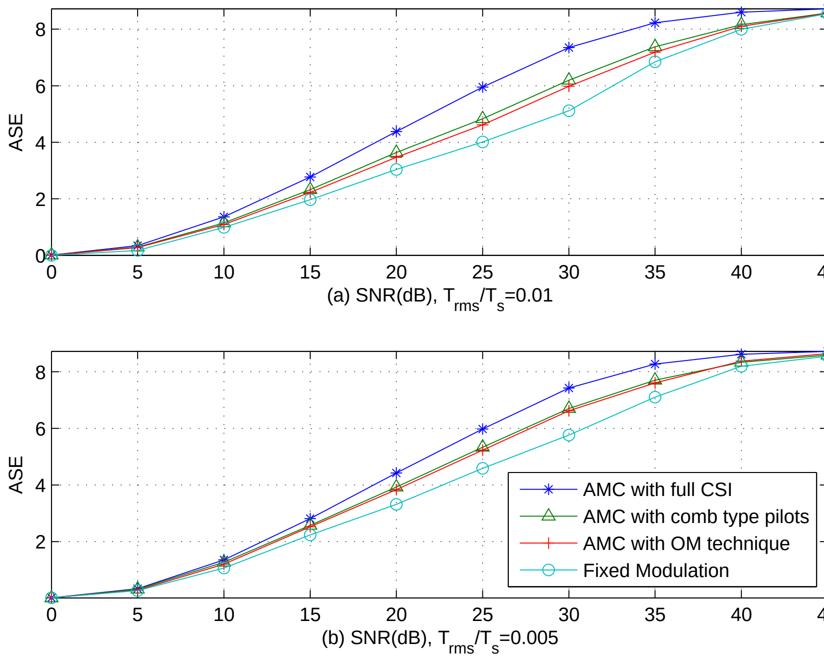

Figure 5.8: ASEs for clustered OFDM systems under 3GPP LTE environments.

techniques.

Fig. 5.8 shows the effectiveness of the proposed scheme in more practical environments. In this figure, the ASE of the clustered OFDM is plotted. The exact same cluster size as the PRB size of 3GPP LTE, 12 subcarriers is considered. Again, the same tendency in the analysis of pilot structures with equidistance is observed in Fig. 5.8. Therefore, the proposed OM technique is suitable for 802.16 or 3GPP LTE using pilots staggered in both time and frequency as shown Fig. 5.6.

5.5 Conclusion

This chapter has presented a channel estimation technique using the order information of subcarrier channel gains under practical discrete ACM OFDM systems. Analytical expressions for the performance evaluation of the OM technique have been derived. The performance of the OM techniques, including BER and ASE, is comparable to that of the comb-type pilot structure, while the required feedback amount is significantly reduced. When $N = 64$ and $L = 16$ corresponding to [8], comparable performance results have been achieved with about 30% feedback reduction compared to that of the conventional comb-type pilot structure. Although this chapter has shown the advantage of the OM technique in a specific example, the performance gain over comb-type pilot structure increases if OM technique is applied to the OFDM systems with a large number of subcarriers, such as IEEE 802.16 or 3GPP LTE, because adaptive resource allocation is typically more effective in larger dimensional systems.

Chapter 6

Conclusion

6.1 Summary

This dissertation has presented link adaptation techniques for wireless OFDM systems in the context of practical constraints, such as complexity and feedback amount. It has developed three different approaches focused on performance enhancement under various constraints. The proposed approaches in this dissertation improve performance of the low SNR or SINR regimes where the performance of systems is most important.

The first approach is "Random Waterfilling", which provides a solution to frequency deficiency problems. The proposed solution is especially focused on systems overlaid with pre-occupied frequency bands, such as the ISM band. For this solution, random waterfilling is proposed for clustered OFDMA systems. The proposed random waterfilling effectively amplifies the multiuser diversity gain in perspective of power allocation so that a meaningful capacity gain is achieved over conventional equal power allocation in the low SNR regime. Through simulations and mathematical analysis, it is shown that the relative gain over static equal power allocation increases as the received SNR decreases. In addition, the analytical upper boundary of capacity was derived to verify that the capacity of the proposed techniques grows such that $\mathcal{O}\left(\log_2 \sqrt{\frac{K}{2}-1}\right)$, with K (the number of users). The proposed random waterfilling algorithm is more effective than equal power allocation in the very low SNR regime.

The second approach is a modified multimode power loading scheme for large dimensional OFDM systems. The proposed power loading scheme circumvents the limits of multi-mode power loading while maintaining its advantages. The proposed technique generates the same optimal power loading configuration as multi-mode power loading technique without recourse to brute-force searches. The proposed technique reduces the required search amount to N, while multi-mode power loading must perform $2^N - 1$ brute-force searches in order to find the best power configuration. Thus, this method works well on a practical level for systems with a large N of subcarriers. The required feedback amount of the proposed technique is only N bits. Furthermore, the proposed technique does not need a shared codebook, so it is able to save the memory space at the transceiver.

The final approach presents a channel estimation technique using order information of subcarrier channel gains in adaptive OFDM systems. The analysis and simulation results show the effectiveness of the OM technique for various adaptive OFDM systems. The performance of the OM techniques, including BER and ASE, is comparable to that of the comb-type pilot structure, while the required feedback amount is significantly reduced. When $N = 64$ and $L = 16$ corresponding to [8], comparable performance results have been achieved with about 30% feedback reduction compared to that of the conventional comb-type pilot structure. The performance gain over comb-type pilot structure increases if an OM technique is applied to the OFDM systems with large numbers of subcarriers, such as IEEE 802.16 or 3GPP LTE, because adaptive resource allocation is typically more effective in larger dimensional systems.

6.2 Future Work

Future work related to this dissertation research should include the following topics:

Application of order mapping technique in multiuser OFDM systems: In multiuser OFDM systems [21, 124], multiuser diversity can be achieved by opportunistic scheduling, such that the user with the best channel (or channel cluster) condition is scheduled for transmission first [27, 112]. However, the scheduler requires full feedback information for whole subcarriers or clusters from all users in order to compare the channel quality. In the same context of the proposed scheme in Chapter 4, the feedback information of each user can be reconstructed by order information. Marginal user diversity is expected compared to conventional opportunistic scheduling, while the required amount of feedback will be significantly reduced. Moreover, this approach can be expanded on the Best-M scheduling [117], a pending solution for the E-UTRA [12].

Mathematical derivation of the optimization: Although channel estimation using OM technique effectively reduces the amount of feedback, the optimal number of pilots for ordermapping technique is required for efficiency. In this context, the optimization problem of the amount of feedback and achievable spectral efficiency needs to be solved.

Bibliography

[1] M. Mouly and M.-B. Pautet, *The GSM System for Mobile Communications.* Paris, France: Telecom Publishing, 1992.

[2] A. Viterbi *et al.*, *CDMA: Principles of spread spectrum communication.* Reading, MA: Addison-Wesley, 1995.

[3] P. Bender, P. Black, M. Grob, R. Padovani, N. Sindhushyana, and S. Viterbi, "CDMA/HDR: a bandwidth efficient high speed wireless data servicefor nomadic users," *IEEE Commun. Mag.*, vol. 38, no. 7, pp. 70–77, Jul. 2000.

[4] T. E. Kolding, F. Frederiksen, and P. E. Mogensen, "Performance aspects of WCDMA systems with high speed downlink packet access (HSDPA)," in *Proc. IEEE VTC Fall 2002*, Vancouver, Canada, 2002, pp. 477–481.

[5] J. G. Andrews, A. Ghosh, and R. Muhamed, *Fundamentals of WiMAX: Understanding Broadband Wireless Networking (Prentice Hall Communications Engineering and Emerging Technologies Series).* Upper Saddle River, NJ: Prentice Hall PTR, 2007.

[6] H. Ekstrom, A. Furuskar, J. Karlsson, M. Meyer, S. Parkvall, J. Torsner, M. Wahlqvist, E. Res, and G. Aachen, "Technical solutions for the 3G

long-term evolution," *IEEE Commun. Mag.*, vol. 44, no. 3, pp. 38–45, Mar. 2006.

[7] *Part 11: wireless* LAN *Medium Access Control (*MAC*) and Physical Layer (*PHY*) specifications: High-Speed Physical Layer in the 5* GHZ *Band*, IEEE Std. 802.11a-1999, 2000.

[8] *Part 11: wireless* LAN *Medium Access Control (*MAC*) and Physical Layer (*PHY*) specifications: Higher-speed Physical Layer extension in the 2.4* GHZ *Band*, IEEE Std. 802.11b-1999/Cor 1-2001, 2001.

[9] *Part 11: wireless* LAN *Medium Access Control (*MAC*) and Physical Layer (*PHY*) specifications: Further Higher Data Rate Extension in the 2.4* GHZ *Band*, IEEE Std. 802.11g-2003, 2003.

[10] R. Nee and R. Prasad, *OFDM for Wireless Multimedia Communications.* Norwood, MA: Artech House, Inc., 2000.

[11] *Standard for Local and metropolitan area networks Part 16: Air Interface for Fixed Broadband Wireless Access Systems*, IEEE Std. 802.16e-2005, 2006.

[12] *Requirements for Evolved UTRA and UTRAN*, 3GPP Std. TR 25.913.

[13] *Physical Layer for Ultra Mobile Broadband (UMB) Air Interface Specification*, 3GPP2 Std. C.S0084-001-0 v1.088.

[14] G. Caire and S. Shamai, "On the capacity of some channels with channel state information," *IEEE Trans. Inf. Theory*, vol. 45, no. 6, pp. 2007–2019, Sep. 1999.

[15] M. R. Souryal and R. L. Pickholtz, "Adaptive modulation with imperfect channel information in OFDM," in *Proc. IEEE ICC 2001*, Helsinki, Finland, Jun. 2001, pp. 1861–1865.

[16] A. J. Goldsmith and P. P. Varaiya, "Capacity of fading channels with channel side information," *IEEE Trans. Inf. Theory*, vol. 43, no. 6, pp. 1986–1992, Nov. 1997.

[17] A. J. Goldsmith and S. G. Chua, "Variable-rate variable-power MQAM for fading channels," *IEEE Trans. Commun.*, vol. 45, no. 10, pp. 1218–1230, Oct. 1997.

[18] A. Leke and J. M. Cioffi, "Impact of imperfect channel knowledge on the performance of multicarrier systems," in *Proc. IEEE GLOBECOM 1998*, Sydney, Australia, Nov. 1998, pp. 951–955.

[19] ——, "Multicarrier systems with imperfect channel knowledge," in *Proc. IEEE International Symposium on Personal, Indoor and Mobile Radio Communications 1998*, Boston, MA, Sep. 1998, pp. 549–553.

[20] A. Czylwik, "Adaptive OFDM for wideband radio channels," in *Proc. IEEE GLOBECOM 1996*, London, UK, Nov. 1996, pp. 713–718.

[21] C. Y. Wong, R. S. Cheng, K. B. Lataief, and R. D. Murch, "Multiuser OFDM with adaptive subcarrier, bit, and power allocation," *IEEE J. Sel. Areas Commun.*, vol. 17, no. 10, pp. 1747–1758, Oct. 1999.

[22] S. Ye, R. S. Blum, and L. J. Cimini, Jr., "Adaptive modulation for variable-rate OFDM systems with imperfect channel information," in *Proc. IEEE VTC Spring 2002*, Birmingham, AL, May 2002, pp. 767–771.

[23] Y. Rong, S. A. Vorobyov, and A. B. Gershman, "Adaptive OFDM techniques with one-bit-per-subcarrier channel-state feedback," *IEEE Trans. Commun.*, vol. 54, no. 11, pp. 1992–2003, Nov. 2006.

[24] Z. Shen, J. G. Andrews, and B. L. Evans, "Adaptive resource allocation in multiuser OFDM systems with proportional rate constraints," *IEEE Trans. Wireless Commun.*, vol. 4, no. 6, pp. 2726–2737, Nov. 2005.

[25] W. Wang, T. Ottosson, M. Sternadt, A. Ahlen, and A. Svensson, "Impact of multiuser diversity and channel variability on adaptive OFDM," in *Proc. IEEE VTC Fall 2003*, Orlando, FL, Oct. 2003, pp. 547–551.

[26] J. Jang and K. B. Lee, "Transmit power adaptation for multiuser OFDM systems," *IEEE J. Sel. Areas Commun.*, vol. 21, no. 2, pp. 171–178, Feb. 2002.

[27] P. Viswanath, D. N. C. Tse, and R. Laroia, "Opportunistic beamforming using dumb antennas," *IEEE Trans. Inf. Theory*, vol. 48, no. 6, pp.

1277–1294, Jun. 2002.

[28] J. P. Pavon and S. Choi, "Link adaptation strategy for IEEE 802.11 WLAN via received signal strength measurement," in *Proc. IEEE ICC 2003*, Anchorage, Alaska, May 2003, pp. 1108–1113.

[29] D. Love, R. W. Heath, W. Santipach, and M. Honig, "What is the value of limited feedback for MIMO channels?" *IEEE Commun. Mag.*, vol. 42, no. 10, pp. 54–59, Oct. 2004.

[30] R. S. Blum, "MIMO with limited feedback of channel state information," in *Proc. IEEE ICASSP 2003*, Hong Kong, Apr. 2003, pp. 89–92.

[31] Y. Rong, S. A. Vorobyov, and A. B. Gershman, "Adaptive OFDM techniques with one-bit-per-subcarrier channel-state feedback," *IEEE Trans. Commun.*, vol. 54, no. 11, pp. 1993–2003, Nov. 2006.

[32] D. Love and R. W. Heath, "Limited feedback unitary precoding for spatial multiplexing systems," *IEEE Trans. Inf. Theory*, vol. 51, no. 8, pp. 2967–2976, Aug. 2005.

[33] P. Svedman, S. K. Wilson, L. Cimini, Jr., and B. Ottersten, "A simplified opportunistic feedback and scheduling scheme for OFDM," in *Proc. IEEE VTC Fall 2004*, Los Angeles, CA, May 2004, pp. 1878–1882.

[34] S. Sanayei, A. Nosratinia, and N. Aldhahir, "Opportunistic dynamic subchannel allocation in multiuser OFDM networks with limited feed-

back," in *Proc. IEEE Information Theory Workshop 2004*, San Antonio, TX, Oct. 2004, pp. 182–186.

[35] Y. Li, "Simplified channel estimation for OFDM systems with multiple transmit antennas," *IEEE Trans. Wireless Commun.*, vol. 1, no. 1, pp. 67–75, Jan. 2002.

[36] W. Yu and J. M. Cioffi, "On constant power water-filling," in *Proc. IEEE ICC 2001*, Helsinki, Finland, Jun. 2001, pp. 1665–1669.

[37] B. Muquet, M. De Courville, G. B. Giannakis, Z. Wang, and P. Duhamel, "Reduced complexity equalizers for zero-padded OFDM transmissions," in *Proc. IEEE ICASSP 2000*, Istanbul, Turkey, Jun. 2000, pp. 2973–2976.

[38] R. Negi and J. M. Cioffi, "Pilot tone selection for channel estimation in a mobile OFDM system," *IEEE Trans. Consum. Electron.*, vol. 44, no. 3, pp. 1122–1128, Aug. 1998.

[39] S. Ohno and G. B. Giannakis, "Optimal training and redundant precoding for block transmissions with application to wireless OFDM," *IEEE Trans. Commun.*, vol. 50, no. 12, pp. 2113–2123, Dec. 2002.

[40] G. Al-Rawi, T. Al-Naffouri, A. Bahai, and J. M. Cioffi, "Exploiting error-control coding and cyclic-prefix in channel estimation for coded OFDM systems," in *Proc. IEEE GLOBECOM 2002*, Taipei, Taiwan, Nov. 2002, pp. 1152–1156.

[41] S. Zeadally and L. Zhang, "Enabling gigabit network access to end users," *Proc. IEEE*, vol. 92, no. 2, pp. 340–353, Feb. 2004.

[42] C. Park and T. S. Rappaport, "Short-range wireless communications for next-generation networks: UWB, 60 GHz Millimeter-Wave WPAN, and ZigBee," *IEEE Wireless Commun. Mag.*, vol. 14, no. 4, pp. 70–78, Aug. 2007.

[43] L. Yang and G. B. Giannakis, "Ultra-wideband communications: an idea whose time has come," *IEEE Signal Process. Mag.*, vol. 21, no. 6, pp. 26–54, Nov. 2004.

[44] D. Porcino and W. Hirt, "Ultra-wideband radio technology: potential and challenges ahead," *IEEE Commun. Mag.*, vol. 41, no. 7, pp. 66–74, Jul. 2003.

[45] M. Z. Win and R. A. Scholtz, "Impulse radio: how it works," *IEEE Commun. Lett.*, vol. 2, no. 2, pp. 36–38, Feb. 1998.

[46] S. Gezici, A. F. Molisch, H. V. Poor, and H. Kobayashi, "The trade-off between processing gains of impulse radio systems in the presence of timing jitter," in *Proc. IEEE ICC 2004*, Paris, France, Jun. 2004, pp. 3596–3600.

[47] M. Z. Win and R. A. Scholtz, "Ultra-wide bandwidth time-hopping spread-spectrum impulse radio for wireless multiple-access communications," *IEEE Trans. Commun.*, vol. 48, no. 4, pp. 679–689, Apr. 2000.

[48] H. Hashemi, "Impulse response modeling of indoor radio propagation channels," *IEEE J. Sel. Areas Commun.*, vol. 11, no. 7, pp. 967–968, Sep. 1993.

[49] A. Batra *et al.*, "Multiband OFDM physical layer proposal for IEEE 802.15 task group 3a," Sep. 2004. [Online]. Available: http://www.wimedia.org/imwp/idms/popups/pop_download.asp?ContentID=6516

[50] J. Balakrishnan, A. Batra, and A. Dabak, "A multi-band OFDM system for UWB communication," in *Proc. IEEE Conference on Ultra Wideband Systems and Technologies*, Reston, VA, Nov. 2003, pp. 354–358.

[51] A. Batra, J. Balakrishnan, G. R. Aiello, J. R. Foerster, and A. Dabak, "Design of a multiband OFDM system for realistic UWB channel environments," *IEEE Trans. Microw. Theory Tech.*, vol. 52, no. 9, pp. 2123–2138, Sep. 2004.

[52] Multiband OFDM Alliance, "MultiBand OFDM Physical Layer Specification," *Release 1.1*, 2005.

[53] D. Love and R. W. Heath, "OFDM power loading using limited feedback," *IEEE Trans. Veh. Technol.*, vol. 54, no. 5, pp. 1773–1780, Sep. 2005.

[54] K. Lie, F. Yin, W. Wang, and Y. Liu, "An efficient greedy loading algorithm for adaptive modulation in OFDM systems," in *Proc. Proc. IEEE PIMRC 2005*, Berlin, Germany, Sep. 2005, pp. 1130–1134.

[55] C. Shin, J. G. Andrews, and E. J. Powers, "An efficient design of doubly selective channel estimation for OFDM systems," *IEEE Trans. Wireless Commun.*, vol. 6, no. 10, pp. 3790–3802, Oct. 2007.

[56] I. C. Wong and B. L. Evans, "Optimal downlink OFDMA resource allocation with linear complexity to maximize ergodic rates," *IEEE Trans. Wireless Commun.*, vol. 7, no. 3, pp. 962–971, Mar. 2008.

[57] A. J. Goldsmith and S. G. Chua, "Adaptive coded modulation for fading channels," *IEEE Trans. Commun.*, vol. 46, no. 5, pp. 595–602, May 1998.

[58] A. Czylwik, "Comparison between adaptive OFDM and single carrier modulation withfrequency domain equalization," in *Proc. IEEE VTC 1997*, Phoenix, AZ, May 1997, pp. 865–869.

[59] G. Stuber, J. Barry, S. Mclaughlin, Y. Li, M. Ingram, and T. Pratt, "Broadband MIMO-OFDM wireless communications," *Proc. IEEE*, vol. 92, no. 2, pp. 271–294, Feb. 2004.

[60] D. Kivanc, G. Li, and H. Liu, "Computationally efficient bandwidth allocation and power control for OFDMA," *IEEE Trans. Wireless Commun.*, vol. 2, no. 6, pp. 1150–1158, Nov. 2003.

[61] B. Yang, Z. Cao, and K. B. Letaief, "Analysis of low-complexity windowed DFT-based MMSE channel estimator for OFDM systems," *IEEE Trans. Commun.*, vol. 49, no. 11, pp. 1977–1987, Nov. 2001.

[62] C. Mutti, D. Dahlhaus, T. Hunziker, and M. Foresti, "Bit and power loading procedures for OFDM systems with bit-interleaved coded modulation," in *10th International Conference on Telecommunications 2003*, Tahiti, Papeete, French Polynesia, Feb. 2003, pp. 1422–1427.

[63] A. M. Wyglinski, F. Labeau, and P. Kabal, "Effects of imperfect subcarrier SNR information on adaptive bit loading algorithms for multicarrier systems," in *Proc. IEEE GLOBECOM 2004*, Dallas, TX, Nov. 2004, pp. 3835–3839.

[64] J. Jang, K. B. Lee, and Y. H. Lee, "Transmit power and bit allocations for OFDM systems in a fading channel," in *Proc. IEEE GLOBECOM 2003*, San Francisco, CA, Dec. 2003, pp. 858–862.

[65] M. S. Alouini and A. J. Goldsmith, "Adaptive modulation over Nakagami fading channels," *Wireless Personal Communications*, vol. 13, no. 1, pp. 119–143, 2000.

[66] K. J. Hole, H. Holm, and G. E. Oien, "Adaptive multidimensional coded modulation over flat fading channels," *IEEE J. Sel. Areas Commun.*, vol. 18, no. 7, pp. 1153–1158, Jul. 2000.

[67] S. Vishwanath and A. J. Goldsmith, "Adaptive turbo-coded modulation for flat-fading channels," *IEEE Trans. Commun.*, vol. 51, no. 6, pp. 964–972, Jun. 2003.

[68] S. Colieri, M. Ergen, A. Puri, and A. Bahai, "A study of channel estimation in OFDM systems," in *Proc. IEEE VTC Fall 2002*, Vancouver, Canada, Sep. 2002, pp. 894–898.

[69] M. H. Hsieh and C. H. Wei, "Channel estimation for OFDM systems based on comb-type pilot arrangement in frequency selective fading channels," *IEEE Trans. Consum. Electron.*, vol. 44, no. 1, pp. 217–225, Feb. 1998.

[70] S. Coleri, M. Ergen, A. Puri, and A. Bahai, "Channel estimation techniques based on pilot arrangement in OFDM systems," *IEEE Trans. Broadcast.*, vol. 48, no. 3, pp. 223–229, Sep. 2002.

[71] M.-H. Hsieh and C.-H. Wei, "Channel estimation for OFDM systems based on comb-type pilot arrangement in frequency selective fading channels," *IEEE Trans. Consum. Electron.*, vol. 44, no. 1, pp. 217–225, Feb. 1998.

[72] H. Minn and V. K. Bhargava, "An investigation into time-domain approach for OFDM channel estimation," *IEEE Trans. Broadcast.*, vol. 46, no. 4, pp. 240–248, Dec. 2000.

[73] J. Kim, J. Park, and D. Hong, "Performance analysis of channel estimation in OFDM systems," *IEEE Signal Process. Lett.*, vol. 12, no. 1, pp. 60–62, Jan. 2005.

[74] Y. Zhao and A. Huang, “A novel channel estimation method for OFDM mobile communication systems based on pilot signals and transform-domain processing,” in *Proc. IEEE VTC 1997*, Phoenix, AZ, May 1997, pp. 2089–2093.

[75] A. Leke and J. M. Cioffi, “A maximum rate loading algorithm for discrete multitone modulation systems,” in *Proc. IEEE GLOBECOM 1997*, Phoenix, AZ, Nov. 1997, pp. 1514–1518.

[76] A. G. Marques, F. F. Digham, and G. B. Giannakis, “Optimizing power efficiency of OFDM using quantized channel state information,” *IEEE J. Sel. Areas Commun.*, vol. 24, no. 8, pp. 1581–1592, Aug. 2006.

[77] A. Gersho and R. M. Gray, *Vector quantization and signal compression.* Norwell, MA: Kluwer Academic Publishers, 1991.

[78] G. E. Oien, H. Holm, and K. J. Hole, “Impact of channel prediction on adaptive coded modulation performance in Rayleigh fading,” *IEEE Trans. Veh. Technol.*, vol. 53, no. 3, pp. 758–769, May 2004.

[79] Y. G. Li and N. R. Sollenberger, “Clustered OFDM with channel estimation for high rate wireless data,” *IEEE Trans. Commun.*, vol. 49, no. 12, pp. 2071–2076, Dec. 2001.

[80] P. Svedman, S. K. Wilson, and B. Ottersten, “A QoS-aware proportional fair scheduler for opportunistic OFDM,” in *Proc. IEEE VTC Fall 2004*, Los Angeles, CA, Sep. 2004, pp. 26–29.

[81] J. Chuang and N. Sollenberger, "Beyond 3G: wideband wireless data access based on OFDM and dynamic packet assignment," *IEEE Commun. Mag.*, vol. 38, no. 7, pp. 78–87, Jul. 2000.

[82] I. Kalet, "The multitone channel," *IEEE Trans. Commun.*, vol. 37, no. 2, pp. 119–124, Feb. 1989.

[83] A. Goldsmith, *Wireless Communications.* New York, NY: Cambridge University Press, 2005.

[84] T. M. Cover and J. A. Thomas, *Elements of Information Theory*, 2nd ed. New York, NY: Wiley, 1992.

[85] J. A. C. Bingham, "Multicarrier modulation for data transmission: an idea whose time has come," *IEEE Commun. Mag.*, vol. 28, no. 5, pp. 5–14, May 1990.

[86] N. Chiurtu, B. Rimoldi, and E. Telatar, "On the capacity of multi-antenna Gaussian channels," *AT&T Bell Laboratories Tech. Report*, Jun. 1995.

[87] E. Martinian, "Waterfilling gains O(1/SNR) at high SNR," unpublished note. [Online]. Available: citeseer.ist.psu.edu/646493.html

[88] E. H. Choi, W. Choi, and B. F. Womack, "Random waterfilling in a clustered multiuser OFDM system," in *Proc. IEEE MILCOM 2006*, Washington, DC, Oct. 2006, pp. 1–6.

[89] K. Seong, M. Mohseni, and J. M. Cioffi, "Optimal resource allocation for OFDMA downlink systems," in *Proc. IEEE International Symposium on Information Theory 2006*, Seattle, WA, Jul. 2006, pp. 1394–1398.

[90] Y. Yu, X. Wang, and G. Giannakis, "Channel-Adaptive optimal OFDMA scheduling," in *Proc. Conf. on Info. Sciences and Systems*, Baltimore, MD, Mar. 2007, pp. 536–541.

[91] I. C. Wong and B. L. Evans, "Optimal resource allocation in the OFDMA downlink with imperfect channel knowledge," *IEEE Trans. Commun.*, vol. 57, no. 1, pp. 232–241, Jan. 2009.

[92] X. Qin and B. R., "Opportunistic splitting algorithms for wireless networks," in *Proc. IEEE INFOCOM 2004*, Hong Kong, Mar. 2004, pp. 1662–1672.

[93] T. Tang, R. W. Heath, Jr., S. Cho, and S. Yun, "Opportunistic feedback in clustered OFDM systems," in *Proc. International Symposium on Wireless Personal Multimedia Communications*, San Diego, CA, Sep. 2006.

[94] S. Patil and G. de Veciana, "Reducing feedback for opportunistic scheduling in wireless systems," *IEEE Trans. Wireless Commun.*, vol. 6, no. 12, pp. 4227–4232, Dec. 2007.

[95] R. Agarwal, V. Majjigi, Z. Han, R. Vannithamby, and J. M. Cioffi, "Low complexity resource allocation with opportunistic feedback over down-

link OFDMA networks," *IEEE J. Sel. Areas Commun.*, vol. 26, no. 8, pp. 1462–1472, Oct. 2008.

[96] P. Banelli, "Theoretical analysis and performance of OFDM signals in nonlinear fading channels," *IEEE Trans. Wireless Commun.*, vol. 2, no. 2, pp. 284–293, Mar. 2003.

[97] H. A. David and H. N. Nagaraja, *Order Statistics.* Hoboken, NJ: Wiley, 2003.

[98] W. Choi, A. Forenza, J. G. Andrews, and R. W. Heath, "Opportunistic space division multiple access with beam selection," *IEEE Trans. Commun.*, vol. 55, no. 12, pp. 2371–2380, Dec. 2007.

[99] C. H. Yih and E. Geraniotis, "Adaptive modulation, power allocation and control for OFDM wireless networks," in *Proc. IEEE PIMRC 2000*, London, UK, Sep. 2000, pp. 809–813.

[100] P. Xia, S. Zhou, and G. Giannakis, "Bandwidth-and power-efficient multicarrier multiple access," *IEEE Trans. Commun.*, vol. 51, no. 11, pp. 1828–1837, Nov. 2003.

[101] Y. Rong, S. A. Vorobyov, and A. B. Gershman, "On average one bit per subcarrier channel state information feedback in OFDM wireless communication systems," in *Proc. IEEE GLOBECOM 2004*, Dallas, TX, Nov. 2004, pp. 4011–4015.

[102] Y. Sun and M. L. Honig, "Minimum feedback rates for multicarrier transmission with correlated frequency-selective fading," in *Proc. IEEE GLOBECOM 2003*, San Francisco, CA, Dec. 2003, pp. 1628–1632.

[103] E. Choi, W. Choi, and B. Womack, "An enhanced multimode power loading algorithm applicable to large dimensional OFDM systems," in *Proc. IEEE MILCOM 2008*, San Diego, CA, Nov. 2008, pp. 1–5.

[104] Y. Yao and G. Giannakis, "Rate-maximizing power allocation in OFDM based on partial channel knowledge," *IEEE Trans. Wireless Commun.*, vol. 4, no. 3, pp. 1073–1083, May 2005.

[105] S. Lloyd, "Least squares quantization in PCM," *IEEE Trans. Inf. Theory*, vol. 28, no. 2, pp. 129–137, Mar. 1982.

[106] R. W. Heath and D. Love, "Multimode antenna selection for spatial multiplexing systems with linear receivers," *IEEE Trans. Signal Process.*, vol. 53, no. 8, pp. 3042–3056, Aug. 2005.

[107] D. Love and R. W. Heath, "Multimode precoding for MIMO wireless systems," *IEEE Trans. Signal Process.*, vol. 53, no. 10, pp. 3674–3687, Oct. 2005.

[108] S. Zhou, Z. Wang, and G. Giannakis, "Performance analysis for transmit-beamforming with finite-rate feedback," in *Proc. Conf. on Inform. Sciences and Systems 2004*, Princeton, NJ, Mar. 2004, pp. 880–885.

[109] K. Huang, B. Mondal, R. W. Heath, and J. G. Andrews, "Multi-antenna limited feedback for temporally-correlated channels: Feedback Compression," in *Proc. IEEE GLOBECOM 2006*, San Francisco, CA, Dec. 2006, pp. 1–5.

[110] G. Jongren and M. Skoglund, "Improving orthogonal space-time block codes by utilizing quantized feedback information," in *Proc. IEEE Int. Symp. on Info. Theory 2001*, Washington, DC, Jun. 2002, p. 220.

[111] ——, "Utilizing quantized feedback information in orthogonal space-time block coding," in *Proc. IEEE GLOBECOM 2000*, San Francisco, CA, Nov. 2000, pp. 995–999.

[112] D. Tse and P. Viswanath, *Fundamentals of wireless communication.* New York, NY: Cambridge University Press, 2005.

[113] J. P. Linnartz, "The tutorial on wireless communication systems." [Online]. Available: http://wireless.per.nl/reference/chaptr05/ofdm/ofdmchan.htm

[114] D. R. Pauluzzi and N. C. Beaulieu, "A comparison of SNR estimation techniques for the AWGN channel," *IEEE Trans. Commun.*, vol. 48, no. 10, pp. 1681–1691, Oct. 2000.

[115] E. H. Choi, W. Choi, J. G. Andrews, and B. F. Womack, "Power loading using order mapping in OFDM systems with limited feedback," *IEEE Signal Process. Lett.*, vol. 15, pp. 545–548, 2008.

[116] *3rd Generation Partnership Project; Technical Specification Group Radio Access Network; Evolved Universal Terrestrial Radio Access (E-UTRA) and Evolved Universal Terrestrial Radio Access Network*, 3GPP Std. TR 36.411.

[117] Huawei, "Overhead reduction of Best-M based CQI reporting," TSG RAN, RAN1 #47, Tech. Rep. R1-063086, 2006.

[118] *Part 11: Draft Standard - Wireless* LAN *Medium Access Control (*MAC*) and Physical Layer (*PHY*) specifications: Enhancements for Higher Throughput*, IEEE Std. 802.11n/D2.00, 2007.

[119] I. Gradshteĭn, I. Ryzhik, and A. Jeffrey, *Table of integrals, series, and products*. San Diego, CA: Academic press, 1994.

[120] M. Nagao and M. Kadoya, "Two-variate exponential distribution and its numerical table for engineering applications," *Bull. Disas. Prev. Res. Inst., Kyoto Univ*, vol. 20, no. 178, pp. 183–210, 1971.

[121] S. K. Wilson, P. Svedman, and J. C. Leonard, "A pruning scheduler for multi-user clustered OFDM systems," in *Proc. IEEE VTC Fall 2004*, Los Angeles, CA, Sep. 2004, pp. 1048–1052.

[122] L. J. Cimini, Jr., B. Daneshrad, and N. R. Sollenberger, "Clustered OFDM with transmitter diversity and coding," *IEEE Trans. Commun.*, vol. 49, no. 12, pp. 2071–2076, Dec. 2001.

[123] *Guidelines for evaluation of radio transmission technologies for IMT-2000*, Recommendation ITU-R Std. M.1225, 1999.

[124] I. Wong and B. L. Evans, *Resource Allocation in Multiuser Multicarrier Wireless Systems*. New York, NY: Springer Verlag, 2007.

Index

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